

Deficit irrigation model-based control of plant growth

Von der Fakultät für Ingenieurwissenschaften,
Abteilung Maschinenbau und Verfahrenstechnik der
Universität Duisburg-Essen
zur Erlangung des akademischen Grades

einer
Doktorin der Ingenieurwissenschaften
Dr.-Ing.

genehmigte Dissertation

von

Friederike Viktoria Kögler
aus
Mannheim, Deutschland

Gutachter:

Univ.-Prof. Dr.-Ing. Dirk Söffker, Universität Duisburg-Essen
Univ.-Prof. Dr. Stefan Siebert, Georg-August-Universität Göttingen

Tag der mündlichen Prüfung: 25. März 2019

DuEPublico

Duisburg-Essen Publications online

UNIVERSITÄT
D U I S B U R G
E S S E N

Offen im Denken

ub | universitäts
bibliothek

Diese Dissertation wird über DuEPublico, dem Dokumenten- und Publikationsserver der Universität Duisburg-Essen, zur Verfügung gestellt und liegt auch als Print-Version vor.

DOI: 10.17185/duepublico/70081

URN: urn:nbn:de:hbz:464-20190425-133924-3

Alle Rechte vorbehalten.

Danksagung

Die vorliegende Arbeit habe ich in der Zeit von 2013 bis 2018 während meiner Tätigkeit als wissenschaftliche Mitarbeiterin am Lehrstuhl für Steuerung, Regelung und Systemdynamik an der Universität Duisburg-Essen erstellt. In meiner Zeit am Lehrstuhl und während meiner wissenschaftlichen Arbeit habe ich sehr viel gelernt, über den Lehr- und Wissenschaftsbetrieb, über Methoden und Gepflogenheiten ingenieur- und naturwissenschaftlicher Forschung, über Studierende, über Kollegen anderer Nationen und nicht zuletzt über mich. Das war eine wunderbare Zeit!

Für diese Gelegenheit und die damit verbundenen Anstrengungen bedanke ich mich sehr, sehr herzlich bei Prof. Dirk Söffker, meinem Betreuer und Mentor. Ich habe mich zu jedem Zeitpunkt sehr ernsthaft betreut, angeleitet und unterstützt gefühlt. Meine Bewunderung gilt außerdem seiner Offenheit für ungewöhnliche Lebensläufe, seiner preußischen Disziplin und seinem unermüdlichen Einsatz für die Ausbildung internationaler Wissenschaftler.

Mein Dank gilt außerdem Prof. Stefan Siebert, der sich kurzentschlossen und beherzt bereit erklärt hat, diese Arbeit zu begutachten, obwohl sie partiell aus einem ganz anderen Fachgebiet kommt. Seit 2015 begegnen wir uns regelmäßig auf der Jahrestagung der Gesellschaft für Pflanzenbauwissenschaften, und es freut mich besonders einen Zweitgutachter aus dieser Community zu haben. Darüber hinaus haben die vielen lieben Kolleginnen und Kollegen mit Ratschlägen und netten Worten zum Gelingen der Arbeit beigetragen; insbesondere auch Yvonne Vengels und Adnan Hasanovic, die mir stets mit einem offenen Ohr und helfenden Händen zur Seite standen.

Schließlich haben eine Reihe weiterer Menschen über viele Jahre hinweg, und auch bereits vor Beginn meiner wissenschaftlichen Arbeit dazu beigetragen, dass ich heute diese Arbeit vorlegen kann: Ohne meine Mutter Marianna von Klinski-Wetzel hätte ich nicht gelernt, selbst zu denken; ohne meinen Vater Prof. Dr. Peter Wetzel hätte ich nicht gewußt, dass man auch in höherem Alter noch promovieren kann; ohne meine Schwester Dr. Katharina von Klinski-Berger hätte ich das Wirtschaftsingenieurstudium nicht angefangen, welches die Grundlage für diese Promotion darstellt, und ohne die Unterstützung meiner Schwiegereltern Dorothea und Klaus Kögler hätte ich den Dipl. Wirt.-Ing. nicht abschließen können; ohne meinen Bruder Henrik von Klinski-Wetzel, hätte ich die Stellenausschreibung im Maschinenbau nicht wahrgenommen und ohne die liebe Jeanette Wissel, hätte ich an Klausurtagen nicht morgens um 6 Uhr zwei beschlafanzugte Kinder zur Weiterleitung an die Schule abgeben können.

Diejenigen jedoch, die mir die ganze Zeit den Rücken freigehalten und Mut gemacht haben, die meine Launen ertragen und Rücksicht genommen haben, die für mich - oder auch an meiner Stelle für sich selbst - organisiert, erledigt und verantwortet haben, sind mein Mann Jochen Kögler und unsere Töchter Hermine und Charlotte. Ohne Euch drei an meiner Seite, hätte ich das alles nicht geschafft, und hätte das alles auch gar keinen Sinn. Euch ist diese Arbeit gewidmet!

Duisburg, März 2019

Friederike Kögler

PS: RIP Molly

Abstract

In the field, irrigation is commonly implemented by the control of water availability in the soil, or in more recent approaches also by measuring the joint water consumption of plant and soil (evapotranspiration) to derive irrigation time and quantity. Here, plant dynamic behavior is not (thoroughly) considered, neglecting the plants' ability to cope with hostile conditions (deficit irrigation). Plant-based approaches have the potential to reflect plant dynamics but are still subject of scientific studies. Here, the target is mostly to detect stress incipience indicating the moment of irrigation initiation, irrigation quantification is is not (yet) possible based on these approaches.

Applying control engineering perception to the irrigation task, the introduction of a suitable model of plant dynamics into irrigation approaches allows directly for plant growth control by means of water input variation. Existing (crop) models (input: agricultural inputs (soil, fertilizer etc.), output: growth/yield) consider plant dynamics due to water deficits very restrictively in form of linear yield reduction functions. A model of plant adaptive behavior including the ability to memorize stress is not available. Hence, a deliberately planned deficit irrigation is not feasible.

In this thesis a novel approach to control plant growth based on water stress training is presented. Here, training is denoted as intended sequencing of water deficit events to control growth behavior. The presented approach is based on deficit irrigation control experiments resulting in a state machine model. In this model, plant adaptive behavior is described in terms of stress level (water deficit detected by the plant), stress memory level (adaptive response aimed at future stresses), and damage level (upper boundary of productive water stress). A quantitative distinction between stress levels is introduced by two new plant-based thresholds: response and recuperation threshold. Open-loop control options are based on the sequencing of two experimentally detected growth performance ranges, i.e. 'hydrological time'-based growth in not memorized states, and 'usage-bound growth' in states with memory. Growth performance in 'usage-bound' range is 47 % higher than in 'hydrological time'-based range. The memorization is proved to be reversible after three days. Statistical hypothesis testing resulted in a proof of concept for the proposed approach.

Additionally, the potential of leaf temperature oscillation analysis for remote water stress state identification is presented. The application of explorative frequency analysis methods on leaf temperature data from the same control experiments resulted in a detection of different superimposed oscillation frequencies. An assumed inference to stomatal oscillation behavior due to water stress could not be proved. However, new insights into leaf temperature behavior based on standard frequency analysis tools are given and discussed regarding application for irrigation purposes.

Kurzfassung

Zur Bewässerung wird in der landwirtschaftlichen Praxis im Allgemeinen die Wasserverfügbarkeit im Boden geregelt (oder gesteuert). Alternativ wird in neueren Ansätzen auch die Messung des gemeinsamen Wasserverbrauches von Pflanze und Boden (Evapotranspiration) für die Ermittlung der Bewässerungsvariablen (Zeitpunkt und Wassermenge) herangezogen. In beiden Ansätzen findet das dynamische Pflanzenverhalten, also die Anpassungsfähigkeit an einen Wassermangel, keine oder kaum Berücksichtigung. Pflanzenbasierte Ansätze hätten das Potenzial, dieses dynamische Verhalten abzubilden, diese befinden sich jedoch noch in der Entwicklung. Hierbei wird bislang im Wesentlichen an der Detektion des Zeitpunktes eines einsetzenden Wasserstressses geforscht, um den Bewässerungszeitpunkt zu ermitteln; die Bewässerungsmenge lässt sich hierbei bislang (noch) nicht berechnen.

Eine Betrachtung der Bewässerungsaufgabe aus regelungstechnischer Sicht impliziert, dass die direkte Regelung/Steuerung des Pflanzenwachstums durch eine Variation des Bewässerungsinputs möglich ist, wenn das System 'Pflanze' in den Regelkreis integriert wird. Vorhandene Modelle hierzu (v.a. crop models; Input: Produktionsfaktoren, Output: Wachstum/Ertrag) beinhalten nur eine sehr begrenzte Darstellung des dynamischen Pflanzenverhaltens aufgrund Wassermangels. Selbiges ist meist modelliert als ertragsmindernde, lineare Funktion. Ein Modell des dynamischen Pflanzenverhaltens aufgrund von Stresszuständen einschließlich Berücksichtigung von Erinnerungsfähigkeiten steht bislang nicht zur Verfügung. Eine gezielte Defizitbewässerung ist demzufolge nicht umsetzbar.

In dieser Arbeit wird ein neuartiger Ansatz zur Steuerung des Pflanzenwachstums auf Basis eines Wasserstressstrainings vorgestellt. Training bezeichnet hierbei die intendierte Ablaufsteuerung von Wasserdefizitereignissen zur Steuerung des Wachstums. Der Ansatz basiert auf den Ergebnissen einer Reihe von Steuerungsexperimenten und dem daraus abgeleiteten Modell eines Zustandsautomaten. In diesem Modell ist das dynamische Pflanzenverhalten dargestellt in Form von 'Stress-Levels' (durch die Pflanze wahrgenommenes Wasserdefizit), 'Stress-Memory-Levels' (Anpassungsverhalten, das auf künftige Stresssituationen ausgerichtet ist) und 'Damage-Levels' (obere Grenze der produktiven Stressanpassung). Die quantitative Unterscheidung der Stresslevels wird über neu eingeführte, pflanzenbasierte Grenzwerte für 'Response' (Anpassung) und 'Recuperation' (Erholung) umgesetzt. Die Steuerungsoptionen ergeben sich auf Basis der zwei experimentell ermittelten Leistungsbereiche für wasserbasiertes Wachstum: Befindet sich die Pflanze in einem Zustand ohne adaptives Verhalten und ohne Erinnerungsvermögen an vergangene Stresszustände, wächst die Pflanze im Leistungsbereich 'hydrologischer Zeit'. Befindet sich die Pflanze hingegen in einem Zustand mit Erinnerungsvermögen, wächst die Pflanze im Leistungsbereich 'verbrauchsabhängigen' Wachstums. Die Wachstumsleistung im

'verbrauchsabhängigen' Leistungsbereich ist um 47 % höher verglichen mit dem des 'hydrologischen Zeit'-basierten Wachstums. Die Dauer des Erinnerungsvermögens konnte mit 3 Tagen festgestellt werden. Hypothesentests bestätigen das Konzept wasserbasierter Wachstumssteuerung.

Neben der Entwicklung des Steuerungsansatzes wird in dieser Arbeit die Verwendung einer Frequenzanalyse von Blatttemperaturoszillationen für kontaktlose Stresszustandsmessungen untersucht. Die Anwendung verschiedener Frequenzanalysemethoden auf erhobene Blatttemperaturdaten der selben Versuchsreihen ergab, dass die Temperaturdaten aus mehreren überlagerten Frequenzen bestehen. Ein Rückschluss auf stomatäres Oszillationsverhalten aufgrund von Wasserdefiziten konnte nicht eindeutig gezogen werden. Dennoch geben die Untersuchungen mit standardisierten Frequenzanalysemethoden neue Einblicke in die Dynamik von Blatttemperaturen unter Wassermangel. Die Ergebnisse werden im Hinblick auf eine Nutzung in Bewässerungsmethoden diskutiert.

Contents

1	Introduction	1
1.1	Deficit irrigation cultivation method	1
1.2	Motivation and tasks of the thesis	2
1.3	Organization of the thesis	3
2	System theoretical description of water stress models	4
2.1	Crop water stress	4
2.2	Object of investigation	8
2.3	System descriptions	10
2.3.1	Soil system	12
2.3.2	Plant system	19
2.3.3	Atmosphere system	33
2.4	Comparative Remarks	40
3	Water-based growth control	44
3.1	Plant adaptation: Missing link to growth control	44
3.2	Deficit irrigation state machine model	46
3.2.1	Experimental set-up	46
3.2.2	Model description	50
3.2.3	Data-driven model parametrization	54
3.3	Open-loop control approach	55
3.4	Proof of concept control approach	57
3.4.1	Experimental validation	57
3.4.2	Hypothesis testing	62
3.5	Summary and discussion	67

4	Remote sensing approach	70
4.1	Leaf temperature oscillations	70
4.2	Leaf temperature measurements	74
4.3	Frequency analysis methods	78
4.4	Frequency analysis results	82
4.4.1	Hypotheses	82
4.4.2	Local Minima and Maxima (MM)	83
4.4.3	Phase Portrait (PP)	85
4.4.4	Cepstrum (CEP)	88
4.4.5	Short Term Fourier Transform (STFT)	90
4.4.6	Wavelet Transform (WT)	92
4.4.7	Stockwell Transform (ST)	95
4.4.8	Hilbert-Huang Transform (HHT)	97
4.5	Summary and discussion	100
5	Summary, Conclusion, and Outlook	105
5.1	Summary and conclusions	105
5.2	Outlook	107
	Bibliography	109

List of Figures

2.1	Causality mapping overview	20
3.1	Picture of experimental setup: Seramis pots	46
3.2	Concept of water stress levels	50
3.3	State machine model of plant behavior due to water stress	51
3.4	Trellis-diagram of stress state trajectories	56
3.5	Illustration of data selection for state determination	58
3.6	Water stress state-based analysis of growth behavior	60
3.7	Water stress state-based analysis of growth performance behavior	61
4.1	Picture of experimental setup: Germination paper	74
4.2	Leaf temperature time series	77
4.3	Local minima and maxima (MM) results	84
4.4	Phase Portrait (PP) results	86
4.5	Cepstrum (CEP) results	89
4.6	Short Term Fourier Transform (STFT) results	91
4.7	Wavelet Transform (WT) results	93
4.8	Stockwell Transform (ST) results	96
4.9	Hilbert-Huang Transform (HHT) results	98

List of Tables

2.1	Causality mapping: Bibliographical references	21
2.2	System-theoretical description of irrigation approaches	42
3.1	Experimental set-up and environmental conditions	49
3.2	Effect of water stress events on leaf appearance	62
3.3	Relation of growth (TLL) to cumulative water content (CWC)	64
3.4	Relation of growth rate (TLER) to evapotranspiration rate (ETR)	64
3.5	Test for mean difference between states	65
3.6	Test for variance homogeneity between states	65
3.7	Comparison of mean growth results	66
4.1	Overview of frequency analysis methods	81
4.2	Overview of frequency analysis results	101

Abbreviations

CEP	Cepstrum
CWC	Cumulative water content
DI	Deficit irrigation
ET	Evapotranspiration
ETR	Evapotranspiration rate
FAO	Food and Agriculture Organization
HHT	Hilbert-Huang Transform
MM	Local Minima and Maxima
PLC	Programmable logic controller
PP	Phase Portrait
ST	Stockwell Transform
STFT	Short Term Fourier Transform
TLER	Total leaf elongation rate
TLL	Total leaf length
UN	United Nations
WC	Water content (substrate moisture)
WT	Wavelet Transform

1 Introduction

According to the UN World Population Prospect [UN 13] the world population will exceed 9 billion in 2050, a raise of more than 20 % compared to today's numbers. The UN Food and Agriculture Organization (FAO) estimates an increase of the global demand for food, feed, and fibre of about 70 % for the first half of this century [UN 09]. Consequently, on the FAO's High Level Experts Forum 'How to feed the World 2050' in October 2009 one of the discussed topics was: *'How much spare capacity in terms of land and water do we have to feed the world in 2050?'* [UN 09]. In addition, an increasing number and dimension of drought events due to climate change threatens food security [SSB⁺14] [FSM18]. Agricultural losses caused by drought are not systematically recorded, but related studies report yield losses of up to 40 % and more [UN 11]. For example the studies [Boy82] [Boy04] commenced in the 1980s stated with regard to USA that drought *'affected crop productivity nearly as much as all the other environmental factors combined.'*

Irrigated agriculture has the potential to contribute substantially to food security if solutions for more moderate fresh water consumption in irrigation can be provided. Irrigated land accounts for about 20 % of the total cultivated land worldwide but it contributes 40 % of the global food production [UL14]. This states the potential contribution which irrigated agriculture might make to raise food security. On the other hand, fresh water withdrawal by the agricultural sector represents about 70 % of the total global fresh water consumption, estimated to exceed the value of 80 % till 2050 [UDW14]. Fresh water availability seriously limits the expansion of agricultural irrigation activities. Consequently, the development of new water saving technologies and procedures is required to reduce freshwater consumption in irrigated agriculture [MV18] [GDLO18]. One option to improve water use efficiency in irrigated agriculture is to improve plant water consumption [RPL⁺17] [AE12].

1.1 Deficit irrigation cultivation method

Deficit irrigation (DI) is a crop cultivation practice allowing to save up to 20-40 % irrigation water at yield reductions below 10 % [ZB04]. Deficit irrigation methods aim at improved water productivity by supplying irrigation amounts below maximum plant water demand and utilizing plant internal dynamic processes leading to more efficient water use [DZYD11] [FS07] [GR09]. Major challenge for the sustainable application of deficit irrigation methods is to control the plants related to their individually optimal water supply state(s). Here, the practical application is limited by two factors:

Controlled system: Agricultural crop water supply state identification is traditionally implemented based on soil system considerations (e.g. tensiometer, soil water balance). In some cases, evapotranspiration-based approaches are implemented [AR07]. Corresponding to control engineering taxonomy, both approaches do not allow to control the plant system, as the plant system is not included into the control loop: Soil-based state identification only considers the soil water availability (no consideration of plant system behavior); evapotranspiration-based state estimation considers the joint soil and plant water consumption (limited consideration of plant system behavior) [KS17]. The feedback control problem of deficit irrigation requires the introduction of the plant system into the control loop, i.e. a model of plant dynamic yield formation behavior subject to water deficits.

Plant-based stress identification: In plant-based approaches, to date the actual plant water supply is not consistently defined in literature and practice. Plant water supply is predominantly circumscribed by using the terms full irrigated/well-watered, mild stress, and high stress. The various determinations selected in different studies are again either soil-based e.g. as percentage of field capacity [LWE⁺17], or evapotranspiration-based e.g. as percentage of crop evapotranspiration [AMI⁺08]. Alternatively, the determination of states is circumscribed by an irrigation water quantity applied to the plants [ZRS⁺10], or by a period of none irrigation [WdCRM10]. In other studies, plant-based variables are investigated to determine plant water supply states, e.g. by a stem water potential value [MAC⁺07] or by a combination of different soil- and plant-based variables [JBP⁺10]. Research is done to develop and validate more general concepts for plant-based water supply state determination e.g. the Crop Water Stress Index (CWSI) [JIRPJ81], [JS08], [BGE09]. Further, most stress-related thresholds for plant-based output variables described in literature refer to stress incipience, i.e. the transition of a well-watered state to a state of first stress symptoms [WA02], [Jon04], [Jon07]. Plant-based thresholds for the transition of a mild stress state to a high stress state, or an evaluation whether the detected symptoms still belong to a mild stress state or already to a high stress state, could only be found in few publications like e.g. [AMI⁺08], [MAC⁺07]. Moreover, if plants are able to cope with certain suboptimal environmental conditions and to recover from deficit situations, the pure identification of a stress incipience is not sufficient to develop control approaches comprising adaptive behavior, as the behavior beyond stress incipience is not covered by the approach.

1.2 Motivation and tasks of the thesis

Aim of this thesis is to prove the concept of a water-based control of plants' dynamic growth behavior (input: water, output: growth). This target is built on a system

theoretical view on systems and relations (cf. section 2), and it is motivated by the control engineering perception of the described irrigation problem: Including water-based plant dynamic growth behavior into irrigation approaches provides the option not only to control water input variables, but also directly to control plant behavior, including growth and yield (controlled system: plant). Here, the missing link to implement water-based growth control for deficit irrigation applications is the introduction of an adequate model of dynamic plant behavior into irrigation control (cf. section 3). Parallel to this part, the investigation of a novel aspect of water stress remote sensing with infrared measurements is implemented (cf. section 4). Here, stress related growth behavior and leaf temperature oscillation behavior are measured simultaneously to examine the observability of water stress by means of frequency analysis methods. This second task addresses the a.m. problem of remote plant-based stress identification directly linked to the proposed control approach.

1.3 Organization of the thesis

In section 2, a comparative description of soil-, plant-, and atmosphere-based irrigation approaches considering the inclusion of dynamic plant behavior is given. Major differences between the three approaches regarding the use in irrigation scheduling are summarized and comparative remarks are given. In section 3 the modeling method and the control approach are introduced. The model of water-based plant growth behavior is implemented as a state machine and includes variables for adaptive plant behavior due to water stress. The proposed open-loop control approach is validated by hypothesis testing. Applicability in the field is discussed. In section 4 leaf temperature measurements (infrared) are investigated with different explorative frequency analysis methods. Results are discussed regarding the use for plant water stress identification in the field. The overall results of the thesis are summarized and discussed in the final section 5. Major parts of this thesis are published or submitted or prepared for publication. Texts originate from [KS17], [KS19a], and [KS19b].

2 System theoretical description of water stress models

In this chapter, state-of-the-art irrigation approaches are described with particular regard to integration of plant dynamic behavior. Initially, a brief introduction to crop water stress behavior is given. Subsequently, the considered irrigation approaches are specified. Then, each system relevant for irrigation (soil, plant, and atmosphere) is analyzed according to system-theoretical taxonomy. Major results are depicted in form of a causality mapping (figure 2.1). Finally, comparative remarks regarding irrigation practice and consideration of plant dynamic behavior are presented and summarized in table 2.2. Major parts of this chapter are published in [KS17].

2.1 Crop water stress

Major physiological processes involved in plant growth and reproduction are water and nutrient uptake and transport, transpiration, photosynthesis, respiration, and metabolic activities. Water in plants acts as solvent, reagent, cell/tissue component, and regulator for turgor and temperature. Plants fresh weight consists of up to 90 % of water [RBGRA14] [Lös01]. Water in plants is involved in plenty of separate physiological processes which are affected if the plant is exposed to water deficits [JS14] [Lös01] [Lar87] [Kut95]. A water deficit for crops occurs if the crop water demand is higher than the crop water uptake at a particular point/period in time. Crop water demand is the water quantity needed by crops to grow optimally [BPH89]. Thus, the water deficit denotes the water quantity lacking due to a plant water uptake quantity below water demand quantity (or a related parameter indicating the extend of undersupply).

Water deficits result in morphologic and/or metabolic deficiencies and developmental disorder (water stress) [Lös01] leading to deviations from the optimality criterium. This optimum criteria is not generally specified [BPH89]. Here, the optimum criteria denotes a physiological development which is not limited due to unsatisfied plant water demand. The time and sequence of appearance as well as the specific significance, detectability and interconnection of water stress effects still receive substantial scientific attention [Cha91] [dSMdS⁺05] [HCZ⁺04] [SG67] [MR11] [WK08]. For example, in [Hsi73] plant processes are investigated regarding their sensitivity to water deficits. Here, sensitivity is defined as point of appearance of process disturbances on a scale of an increasing water stress indicator: The decreasing plant tissue water potential. The water potential is specified in pressure units (e.g. in bar) and it is a representation of water availability as well as the driving force for water

movements (cp. section 2.3.1). The detected sensitivities are stated to range from very high e.g. for cell growth and protein synthesis, to low e.g. for sugar accumulation.

As another example, in [SRH⁺09] it is stated that leaf expansive growth is considered to be the plant process most sensitive to water deficits, whereas stomatal conductance and senescence acceleration are considerably less sensitive. In [MJS⁺10] instead the main limitation to photosynthesis and growth is ascribed to stomatal conductance variations, which is directly affected by soil water availability for plants (soil water potential). Hence, the particular significance of e.g. stomatal conductance for plants being exposed to a water deficit seems not to be unambiguous if investigated in different test settings or environments. Further, in [CLL⁺09] [Blu96] the options and constraints for the identification of unambiguous cause-and-effect-chains of stress effects are addressed. Wilting symptoms for instance could result from a water deficit but also from soil salinity. A rise of leaf temperatures could indicate water deficits (abiotic stress) but also signalize an early viral infection (biotic stress) [CLL⁺09]. This means, that (water) stress responses can not (yet) unambiguously be assigned to causes. Further, interconnections between separate stress effects cannot fully be explained. Moreover, water stress effects change in time: Unfavourable environmental conditions cause initially reversible modifications in development which turn to be irreversible as stress level exceeds a threshold level [Lös01].

Summarizing, water deficits result in dynamic plant behavior (stress responses/effects) differing in time of appearance, dimension of disturbance, and degree of process interconnection. Further, crop responses to water deficits are not readily detectable or unambiguously isolatable.

Time behavior of plants as response to a water deficit is investigated in several studies [AMI⁺08] [AAKHS14] [CBM⁺14] [DHR00] [CPM⁺02]. In [AMI⁺08] the root dynamics of young peach trees submitted to different deficit irrigation regimes are investigated. In this study root dynamics denote the time response of the considered root system variables due to a varying water supply. The results show considerable differences in root length density between the trees exposed to continuous deficit irrigation, side-alternating irrigation (partial root zone drying), or fully irrigated comparative trees. On the other hand, a similar root dynamics (increase/decline of root growth per calendar month) was determined for all three irrigation treatments. This implicates that a presumable causality between water availability and root morphology of the trees does exist. This presumable causality was not determined for the relation of irrigation treatments to root dynamics for this study. In [AAKHS14] the effects of different deficit irrigation schedules on yield, tuber size distribution, and water productivity (in terms of irrigation water consumption related to potato yield) of two potato cultivars are described. Results show that continuous deficit

irrigation generally outperforms side-alternating irrigation referring to total tuber yield, similarly for both cultivars. Irrigation water consumption in deficit irrigation treatments were considerably lower than full irrigation (approximately 30 %) at only slight yield reductions (4-7 percent). Dynamic deficit irrigation treatments (decreasing irrigation amounts per irrigation event in time) shows higher water productivity compared to static irrigation treatments (steady irrigation amounts). This implicits a considerable potential for irrigation water savings for deficit irrigation at steady yields, particularly for continuous deficit irrigation in potatoes, and even more so if a dynamic deficit irrigation is applied. In [CBM⁺14] the effects of drought stress timing on grain yield are investigated. Results show that 'total grain yield' is more sensitive to both timing and severity of water deficit compared to other yield factors (screening, thousand-seed weight). Further, total grain yield reduction was higher when water deficits occur in advanced developmental stages (e.g. grain filling stage) compared to early (vegetative) stages. This implicits a presumable causality between time of water deficits (related to developmental stages) and the magnitude of yield reductions, as well as between time of water deficits and the particular yield factor.

Beyond that, in [DHR00] soybean plant characteristics indicating the occurrence of water stress are investigated. The results of a subsequent measurement of morphological characteristics (e.g. mean internode length) and yield factors (e.g. number of pods) indicate the option to reconstruct dependencies between irrigation timing, physiological development, and yield components. Finally, in [CPM⁺02] photosynthesis and growth processes as well as stress defense/adaptation mechanisms of plants being exposed to a water deficit in the field are described. Particular adaptation processes under water deficit (e.g. a rise in root-shoot ratio or a down-regulation of photochemistry) are discussed regarding the potential to reduce water deficit impacts. Further, in the comparative study [ZB04] it is stated that efficiency of water use by plants is generally higher under water deficit conditions. Deficit irrigation would allow for up to 20-40 percent potential savings of irrigation water. In [DZYD11] crop management practices like deficit irrigation exploiting '*the drought stress physiology of plants to deliver improved water productivity without sacrificing crop yield*' are described. It is mentioned that a controlled water deficit can increase harvest index, defined as percentage of marketable crop yield of total above ground biomass. Additionally, in [CZF⁺10] a potential rise in product quality for grapes under moderate water deficit is identified. On the other hand, in [GR09] it is stated that deficit irrigation practices necessitate consolidated knowledge of crop water deficit responses, which differ substantially depending on genotype and phenological stage. It is proposed to combine field research with modeling of crop water productivity. The study [DZYD11] emphasizes particular caution relating to imprecise irrigation techniques. The authors state that crops under water deficit are more sensible to additional water stress. It is therefore proposed that sensing of plant water deficit might be combined with precision irrigation.

Summarizing, the dynamic behavior of crops being exposed to a controlled water deficit implies the potential to reduce considerably water consumption in agricultural irrigation at steady yields/revenues. In contrast, the exploitation of this potential requires particular knowledge of the dynamic behavior of crops being exposed to water deficits as well as of the dynamic properties of the irrigation techniques specifically applied.

Crop (water) stress is defined as reaction/response to a disturbance stimulus [Lar87] [Lev80]. Here, distinction is drawn between

- the disturbance stimulus affecting the system (stress), and
- the stimulus response of the system (strain).

The relation between stress and strain is a specific function describing the mode of operation of a specific disturbance stimulus. The authors of [Lar87] [Lev80] describe general stress resistance strategies of plants. These strategies are explained based on mechanical principles. The mechanical example of a weight hanging at an elastic cord is employed. Stress is induced to the system by increasing the weight. The stress resistance is determined by relating the stress value (increased weight) to the strain value (the resulting elongation of the cord). Based on this example the authors distinguish between two major stress reaction strategies:

- Stress avoidance by reducing the stress weight, and
- stress tolerance maintaining operativeness despite the stress weight. Stress tolerance results from
 - strain avoidance like augmenting the cord resilience, or from
 - strain tolerance, i.e. acceptance of an increased strain without injury. Strain tolerance is additionally discerned into two regeneration options:
 - * Strain (or injury) reversibility, and
 - * strain repair.

Translated to crop water deficits the meaning of stress avoidance is for example making efforts for increased water uptake. Stress tolerance in contrast can either be achieved by improved water utilization (strain avoidance), or by bearing limitations in operational capability with prospect of regeneration (strain tolerance). Regeneration in turn could either be attained by strain reversibility e.g. resurrection after drought, or by strain repair e.g. restoration of drought injuries. The described categories

formalize the handling of the plant system internal dynamic responses supposed to ensure the plants survival and/or reproduction. Here, 'stress' is defined as plant system external stimulus (i.e. the water deficit) leading to a stress response of the plant system (i.e. the plant water stress).

Further, in [Tar96] two crop water stress definitions are distinguished with respect to the consideration of plant dynamics:

- Water stress is described as an imbalance between water supply and crop water demand (water deficit). Solely soil/air water status at the plants boundaries are considered (feed forward). The plant internal regulation mechanisms are not taken into account.
- Water stress is defined based on plant water status measurements (e.g. leaf turgor sensing). This approach implicitly includes internal control mechanisms (feed back) to sustain the plant water status also under deficit conditions.

Thus, in [Tar96] the term 'stress' is defined either as plant external water (supply) deficit (likewise the definition in [Lar87] and [Lev80]), or as a plant internal water (supply) status differing from a desired benchmark, e.g. the parameter values of unstressed comparative plants [SBMH02] [Lar01].

Hence, the parameters of crop water stress are mainly defined by (a) the water supply/availability, (b) the water demand of the plant, and (c) the specific dynamic plant behavior (plant water stress response due to a water deficit). The detection, time, and quantification of irrigation necessities can either be derived from a plant system external water supply deficit, or from a plant system internal water supply status.

2.2 Object of investigation

In this thesis irrigation approaches and water (stress) models used for irrigation purposes are comparatively described according to a system-theoretical taxonomy (structure and logical functionality). Three irrigation approaches are known [JS14] [PKM09] [ZP13]:

- Soil water status-based irrigation,
- plant water status-based irrigation, or
- atmosphere water status-based irrigation.

All methods employ a 'water model' comprising system states, inputs (e.g. weather data, soil characteristics), and outputs. Here, the output variables of the models are the irrigation variables 'irrigation quantity' and 'irrigation time'.

In addition, crop models are increasingly investigated for their use in irrigation management [Ade04] [GGH⁺07] [GVFM⁺09] [SS09] [TSSA⁺13]. Models of this type describe the relation of crop yield as a function of growth factors as well as of management and environmental impacts. Crop models commonly contain a number of sub-models (modules) describing plant development, leaf area index (LAI) dynamics, biomass production, yield formation, as well as water and nutrient balances. Crop models differ in their particular focus [BWB06]. For example, the model APSIM (agricultural production systems simulator) [KCH⁺03] focusses on soil dynamics describing the time behavior of soil based processes with regard to crop production. Contained are modules for transpiration, phenology, biomass acculation, leaf area development, senescence, crop nitrogen, and plant death [BWB06] [CUS⁺] [HHd⁺14]. The model STICS (simulateur multidisciplinaire pour les cultures standard) [BGJ⁺03] emphasizes on farming practices and contains modules for phenology, shoot growth, yield formation, crop management, root growth, water and nitrogen balance, as well as water, nitrogen, and temperature transfers [BWB06] [BGJ⁺03]. The model AquaCrop (the crop water productivity model developed by the Land and Water Division of the United Nations Food and Agriculture Organization (FAO)) [SRH⁺09] addresses particularly the aspect of water availability with modules for canopy development, stomatal conductance, canopy senescence, and harvest index [SRH⁺09]. The model DAISY (danish simulation model) [AH00] considers environmental aspects and describes the relation of crop yield to the water balance, nitrogen balance and losses, soil organic matter dynamics, crop growth, and crop management strategies [BWB06] [AH00].

The water sub-model (water module) in crop models maps the water related processes involved in crop growth, development, and yield formation. It describes crop yield as a function of water consumption, *ceteris paribus*. Water deficits (and other abiotic stresses) are introduced in crop models by empirical, limiting factor functions. These functions represent the disruptive effects of stresses on plant processes resulting in reduced yields [BWB06]. Output variables of crop models are yield factors (e.g. total yield, harvest index). The variation of the model input variables for irrigation time and/or quantity is used to depict the causality between water supply and yield factors. Vice versa, the (optimal) value(s) of the input variables for irrigation may be derived by using a crop model. In this contribution the objects of investigation are the above mentioned three irrigation approaches as well as the water sub-models (modules) of selected crop models.

2.3 System descriptions

Aim of the survey is to provide a comparative overview of modeling pathways chosen by modelers to map water (stress) processes. The descriptions are organized according to a system-theoretical concept. The employed terms and definitions are used according to a system theory-oriented control engineering taxonomy. Models deployed in control engineering are used for:

- The prediction of system behavior (e.g. quantification of yield reductions due to water stress),
- the design of control interventions (e.g. model-based irrigation control),
- the supervision of states/variables (e.g. detection of incipient water stress), and
- the diagnosis of processes and faults (e.g. attribution of physiological effects to water stress) [Lun03].

The validity of system-theoretical considerations not only for technical but also for biological systems is commonly accepted [Lun03] [Wie61] [Von68] [Bos04] [ABB⁺09] [HJ98] [BJR11]. The used terms are defined as stated below (closely related to [Lun03] [Bos04]):

- **System:** Subset of the real world consisting of components/elements and being delimited to the surrounding environment by system boundaries. It may be seen as abstract device or unit (also as a technical substitute) in which processes occur. It can be described as a mathematical operator (S) transforming input variables into output variables.
- **System variables:** These are input variables, output variables, and state variables. Systems may have one or more of all variables (input, output, state).
- **Input-/output variables:** The input variable(s) affect the (inner) state variable(s). If so, the control of the system state(s) may be realized by regulating the input variable(s) (controllability). The output variable(s) are variables varying in time due to a system internal process. The chosen output variable(s) are affected by the (inner) state variable(s) as well as by the input variables directly. If so, the reconstruction of system state(s) may be realized by interpreting the output variable(s) (observability) using a model of inner connections.
- **State variables:** State variables are all system (internal) variables determining the system state. State variables are necessary for an unambiguous and non-redundant description of the system state(s).

- System state: The state of a system is described by a scalar or a vector as a function of time containing all state variables.
- Process: An operation during which the values of one or more system variables (state variables and/or output variables) change dynamically. This operation may be physical, chemical, biological, technical, or even social, psychological etc.
- Dynamic: System variables (state variables and/or output variables) change in time due to a process. Static systems in turn show approximatively no time-variable change of the variables.
- System behavior: Comprises the time responses of the state variables and/or of the output variables of the system (system dynamics) relating to the specific value of an input variable or to a specific control task.
- Input/output signals: Signals are measured values and expressed in physical units. Input-/output variables may be described or measured by input-/output signals.
- System structure: The system structure is denoted by system elements, boundaries, and implicitly the assumptions made by the modeler, largely independent of concrete variables. A common representation of a system structure is a block diagram with systems as blocks and signals as arrows. In this case the block diagram denote the topology connecting the system components to one system with a given topology as (inner) system structure.

System descriptions presented below are structured as follows: First, in this section three subclasses as sub-sections related to 1, 2, and 3 are distinguished: Soil system, plant system, and atmosphere system. This division is based on the review of numerous publications on different crop models and irrigation scheduling approaches resulting in this common distinction of system types [Han02] [JGG⁺11] [KHMW07] [Pas82] [WR96]. This distinction is based on the delimitation of the respective systems from the surrounding environment, so by the definition of system boundaries. Second, each sub-section comprises the description of the particular (real/physical) system structured by the above defined system-theoretical aspects: System boundary and components, system states, system variables and related signals, as well as water related processes. Third, modeling approaches for irrigation purposes relating to the respective system are briefly introduced. Finally, the conversion of system output variables into the irrigation variables 'quantity' and 'time' is depicted in the related graphic 'causality mapping overview' for the different modeling approaches.

2.3.1 Soil system

Boundaries, components: Soil systems represent a subset of the root zone defined as the water-bearing soil area below soil surface and accessible for most plant roots [US 05]. Boundary setting for soil systems aims at demarcating an area around the plant's roots having influence on water supply and uptake by plants. System boundaries exist to the plant system (root surface) and to the atmosphere (soil surface). However, soil system considerations for irrigation or crop modeling differ in defining system boundaries volume and depth. In [ETH⁺04] for example soil moisture measurements in 0.3 m steps up to 1.50 m depth are compared with soil water simulation results of three crop models (CERES, WOFOST, SWAP). In the study [CVBJ14] in turn soil system boundaries are defined for a single maize plant considering 1125 cm² as horizontal dimension and soil horizons up to 120 cm depth. In [SRK⁺15] soil samples in 0.30 cm steps up to 90 cm depth are investigated related to soil water content measurements at 15 cm, 45 cm and 75 cm depth. In [BO07] again case studies with different legumes were conducted relating to soil system depths of up to 40 cm. It can be summarized that boundaries for soil systems are not universally defined in terms of depth or size and depend on crop specific root dimensions. The upper boundary only is defined naturally by the soil and roots surface.

Soils consist of anorganic components (minerals, rocks) and organic components (plant remains, soil organisms). The composition of soils is spatially and temporally not homogenous because of the soil specific formation process. In practice, soils and soil layers (horizons) can be classified based on a defined taxonomy for main layer, primary bedrock and organic substrate, acquired properties, characterization of bedrock, and horizon attributes [UN 06] [GSS⁺97] [ABF⁺10]. Additionally, soil components may be subdivided into a solid (anorganic/organic components), liquid (water, solutes), and a gaseous phase (soil pores). Soil specific composition (components and phases) determines grain size, bedding, pore size distribution, organic matter, pH value, soil moisture, solubility of substances, and therefore all related soil water processes like leaching [ABF⁺10] (cp. subsections below). This means, the consideration of a soil system always comprises a certain heterogeneity and makes therefore demands on the selection and demarcation of sites and on the points of measurement.

System state, variables, signals: Soils have the ability to hold water against gravity. This ability is mainly based on capillary forces and adsorption which hold the water in the soil pores. The smaller the soil pores are, the stronger the water is bond to the soil against gravity [GSS⁺97] [ABF⁺10]. The water quantity actually held by a soil against gravity differs between soil types and spatially within a soil section [ABF⁺10] [AHMU04] [ZTZ⁺14] [ASRHB13]. These differences result from site specific soil composition c (e.g. organic matter) and structure s (e.g. clay,

sand), hydrologic processes h (e.g. water table depth), and soil cultivation impacts i (e.g. plowing) [BWB06] [GSS⁺97] [Jon04]. Assuming totality of the mentioned state variables, the water status of a soil system (wss) can be described by the vector $\mathbf{wss}=[c,s,h,i]^T$.

The maximum water storage ability of a soil is expressed using the term field capacity [SBMH02] [ACB15]. Field capacity is defined as the water quantity which a certain, initially saturated soil is still able to hold against gravity after 2-3 days [VH49]. It is defined on the basis of a soil specific water drainage time, which depends on the soil properties, initial water content, and water depth [Nac98]. Field capacity delimitates the upper threshold of soil water availability for plants. The soil water content at which plants cannot extract any more water from the soil is represented by the term permanent wilting point [SBMH02] [ACB15]. It is defined as the soil status at which the water in all soil pores larger than 2 micrometers is dried-out and the remaining water is bond to the soil with up to 15.000 hPa or 15 bar [GSS⁺97] [ABF⁺10]. The permanent wilting point represents the lower limit of soil water availability for plants [SBMH02] [ACB15]. The water quantity stored in the soil between the thresholds 'field capacity' and 'permanent wilting point' is represented by the term 'water holding capacity'. It describes the water quantity potentially available for plant water uptake [SBMH02] [ABF⁺10]. In practice, soil water contents are commonly indicated in percent of field capacity [Mas02] [Bay08].

Different output variables expressing the soil system water status for irrigation are given in literature:

- Soil water content (quantity) and
- soil water potential.

Soil water content represents the total water quantity contained in a soil sample in terms of litres [l] or gram [g]. This output variable is described in physical units for

- weight [g/g] or volume [l/g] [Jon07],
- electrical conductivity [S/m] or resistivity [Ω] [AHMU04], or
- permittivity [F/m] [KCB13].

Soil water potential represents the tension at which the water is bond to the soil [Kut95] [Von71] [DO05]. The term 'water potential' is a thermodynamic parameter considering the chemical potential of water and its partial molal volume [Jon07]. The term is an expression of the water saturation of a system. It is used as an uniform expression of water availability in different systems (soil, plant, or atmosphere)

and of water movements within or between systems. Therefore, it is applicable for cross-system considerations. Water movements arise if water potential gradients occur e.g. at places of evaporation. Water moves from the place of a high water potential to the place of a low water potential [SBMH02] [DO05].

The output variable 'soil water potential' is described in

- pressures [MPa] or energy per unit volume [J/m³] [SBMH02] [Jon07] [Bit10],
- energy per unit mass [J/kg] [Bit10], or
- weight [cm watercolumn] [Bit10].

The determination of the 'soil water quantity' contained in a soil sample implicates a potential direct conversion of the calculated actual soil water deficit (in terms of [l/g] or [g/g]) into the input variable 'irrigation quantity' in terms of [l/m²] (irrigation perspective): Field capacity is specified in [%] soil weight, in [%] volume, or in [mm] water in the root zone. Here, the conversion is: One volume percent equals 1,5 x weight percent equals 1mm water per 1dm soil depth (equates to [l/m²/dm]) [Mas02] [Bay08]. In contrast, the determination of the 'soil water potential' permits the assessment of the actual soil water availability for plant water uptake (crop perspective): Plants have to expend energy to mobilize the water bond to the soil (cp. chapter plant system). Hence, the soil water potential describes a tension which the plants have to exceed by a relatively higher (negative) plant water potential in order to extract the water from the soil [JS14] [SBMH02] [Bit10]. As plant species differ in their ability to extract water from soils [SBMH02], irrigation is indicated at different soil water potential values for different crops or cultivars. This includes, that the soil water status relevant for crop water uptake is not represented by the output variable 'soil water content' in terms of [l/g] or [g/g]. Here, the determining factor is a ratio of 'soil water potential' to 'plant water potential' [Bit10].

Soil water potential and soil water content are specifically correlated relating to soil type/properties. Soils with a higher share in small soil pores (e.g. clayey soils) or in organic matter hold a higher total water quantity than soils with bigger soil pores (e.g. sandy soils) or a smaller share in organic matter at an equal soil water potential [SBMH02] [GSS⁺97] [ABF⁺10]. The correlations are represented in empirical soil water retention curves which are characteristic for different soil types/properties [ABF⁺10] [Buc07] [SR86]. These curves depict at which water potential value a certain soil type holds/stores which quantity of soil water. Thus, these water retention curves represent the conversion of water potential values (crop perspective) into water quantity values (irrigation perspective) for each soil type. Based on these soil water retention curves, the measurement of a soil water potential

signal permits the assessment of the water quantity stored in the soil, and vice versa, provided the soil type/properties are known [Bit10].

It can be summarized from the cited facts:

1. The sole measurement of a total soil water quantity/content (irrigation perspective) without knowledge of the particular soil properties/type does not suffice to detect the soil water quantity available for plant water uptake. Therefore this approach does also not permit to derive neither irrigation quantities nor irrigation timing directly based on the output variable value alone. Only if soil type/properties are known the sensed soil water content allows the assessment of soil water quantity available for plant water uptake.
2. Further, the sole measurement of a soil water potential (crop perspective) permits to assess whether crops are still able to extract water from the soil at the time of measurement without knowledge of soil type/properties, provided the plant water potential is known. Therefore it is also possible to derive irrigation timing directly based on the output variable value alone, as investigated for example for onions in [SFS98]. On the other hand, irrigation quantities cannot be assessed directly based on the output variable value alone.
3. From these facts it can be concluded, that the knowledge of the soil types/properties is a prerequisite for the quantification of irrigation events. For practical applications, empirical data on soil types and compositions for different regions of the world [UU75] as well as corresponding water holding capacities [vGTM05] [RBF⁺08] are available.

Processes, dynamics: Soil water status changes with respect to time result from water movements into, within, and out of the considered soil system. These movements are

- water intake to the system by
 - precipitation and irrigation, as well as by
 - capillary rise from deeper soil layers/the groundwater,
- water release of the system by
 - deep percolation,
 - evaporation, and
 - water uptake by plants, and

- water transportation within the soil compartment under consideration,
 - vertically by percolation, and capillary rise, and
 - horizontally by subsurface lateral flows [SRH⁺09] [HDCL12].

Water movement on the soil surface (water run-off) has to be distinguished with respect to the place of infiltration: Water run-off on the soil surface results from precipitation/irrigation if soil's ability to absorb water is insufficient to drain it at the point of water inflow. It only accounts for water intake to the soil system, as long as the run-off water infiltrates into the soil system internal soil compartment and does not run off the soil system surface by passing the defined external system boundary to the ambient soil.

Water intake by precipitation and irrigation is denoted as infiltration. It is defined as seepage water percolating top down into the soil. Infiltration is generated by gravity [ABF⁺10]. Water intake by capillary rise represents the inverted process of infiltration and is defined as water from the groundwater, backed-up water, or adhesive water moving upwards against gravity or laterally to plant roots. Capillary rise is caused by a water potential gradient between points of higher to points of lower water potential [ABF⁺10]. Water release by deep percolation is defined as seepage water percolating downwards out of the considered soil system (e.g. out of the root zone). Deep percolation is induced by gravity [ABF⁺10]. Water release by evaporation comprises the vaporization of water in the topmost soil layer and its diffusion out of the soil system into the atmosphere. Evaporation is caused by a water potential gradient between soil and air [ABF⁺10]. Water release by water uptake by plants includes the soil water absorbed by the plants roots. Plant water uptake is induced by an osmotic gradient between root and soil [JS14] [SBMH02] [ABF⁺10]. Water transportation vertically by percolation and capillary rise is identically to the processes of deep percolation and capillary rise but restricted to the area within the system boundaries. The distinction into system internal and external processes is of relevance if soil systems are not considered to be homogenous. Water transportation horizontally by subsurface lateral flows are defined as percolating water retained and redirected laterally downslope by a less permeable soil layer [HDCL12]. Horizontal water transportation is also caused by gravity.

It can be summarized that the soil water status related processes (water intake, transport, and release) are mainly propelled by water potential gradients (bottom up), gravity (top down), and at the soil-plant boundary by an osmotic gradient.

Soil water potentials are influenced by a mix of gravitational, matric, pneumatic, thermal, and osmotic effects [SBMH02] [DO05]. The dynamics (emergence and

changes) of water potential gradients in soils are mainly induced by soil system water releases at the soil boundary to the atmosphere (evaporation) and to the plant (water uptake) [ABF⁺10]. The release of water at the boundary layer of the soil results in a drop of water potential in this area. The resulting water potential gradient generates soil water movements from the place of high water potential towards the place of lower water potential [SBMH02]. The extent (quantity and speed) of the water movement depends on the scale of the water potential gradient and on the water conductivity/permeability of the individual soil [ABF⁺10]. The latter depends on soil type/properties and on soil water content [Jon04].

Models: Basic idea to employ soil system-based models for irrigation purposes is to control the soil water availability for crops in order to detect and balance a plant external water (supply) deficit [PKM09] [Rit98]. For soil water status changes in [JT98] three model classes are described:

- The first group divides an individual soil into layers with approximately homogenous hydraulic/root system characteristics. For each layer an initial mean soil water content/potential is measured. The water states are determined for each layer using commonly the Richard's Equation [Ric31]. The equation describes seepage flows of fluids through porous material based on data for phase saturation, pressure of the fluid, and hydraulic conductivity of the medium [ETH⁺04] [ABF⁺10]. Water movements between layers are determined based on gradients of the volumetric soil water content or of the soil water potential [ETH⁺04] [GA11]. The description and quantification of the dynamics of water movements in the Richard's Equation is based on Darcy law (Henry Darcy, 1803-1858). It states that the flow rate per distance per time is proportional to a conductivity coefficient and to the water potential gradient [ABF⁺10]. As an alternative to Richard's Equation, water movements may be described using a capacity concept. Water movement occurs towards an unsaturated soil compartment as long as the known, soil specific water holding capacity is not reached [ETH⁺04]. The soil water states at different times are determined using a water balance. The latter is calculated by adding the water intake quantities to the initially measured water content, and by subtracting water release quantities, correspondingly [TM57] [KS00]. This approach is used for example in the crop model CERES [KHMW07] [ETH⁺04] [Rit98].
- The second group of models as classified in [JT98] approximates the computed soil water status by measuring once the soil water output variable in a defined rooting zone without dividing it into different layers. Here, the total root zone is assumed being homogenous in its entirety. Soil water states at different times are calculated as well using a water balance. This approach is used for example in the crop model AquaCrop [RSHF12] or in the water balance simulation model ISAREG [RCB07].

- The third group of models in [JT98] deduces the actual soil water status from a sensed plant water output variable: The predawn leaf water potential. The latter is assumed to equal the soil water output variable 'soil water potential' at this time of day [JT98] [WA02]. This method is investigated for tree irrigation in [AAC⁺99]. Strictly speaking, this method is based on a plant system output variable (cp. chapter plant systems).

Input variables for soil system-based water balance model (first and second a.m. groups) are: (a) An initially sensed soil water content, (b) sensed or modeled water intake quantities for precipitation, irrigation, and capillary rise into the considered soil compartment, and (c) sensed or modeled water release quantities for percolation, evaporation, and plant water uptake. Output variable of a soil system-based water balance model is the resulting soil water content. The value of this output variable is used, on the one hand, in crop models as input variable for a plant system (representing the soil water content available for plant water uptake) and/or for an atmosphere system (representing the soil water content available for evaporation). On the other hand, the value of the output variable is used in irrigation approaches to indicate quantity and/or time of irrigation events directly from the determined soil moisture/water content status compared to fixed thresholds [GE01] [LMM⁺14] [SDO⁺13]. The quantification of the water amount to be applied per irrigation event is derived by the difference between the actual value of the soil water output variable and the upper reference value of the soil water output variable (e.g. 80 percent of field capacity or the corresponding water potential (hPa) value of the specific soil), adopted to the actual root depth of the crop [Bay08]. The time of irrigation events derived from soil water states is determined by an actual value of the soil water output variable falling below a lower reference soil water output variable threshold. In practice, this lower threshold is commonly at 40-50 percent of the maximum water holding capacity (field capacity) of the individual soil [Bay08] [Rog15]. In terms of water potentials irrigation is recommended to start at 300-400 hPa for sandy soils, and at 500-800 hPa for clayey soils [Bay08]. The precise quantity in terms of [l/m²] to be applied to the soil to achieve this targeted soil water status depends on above mentioned individual soil properties, the initial soil moisture, and root zone depth. At an initial soil moisture/water content between 50 and 80 percent of field capacity the irrigation amount for most crops range between 2,6 and 7,9 [mm/m²/dm depth] [Mas02] [Bay08]. The frequency of irrigation events based on soil states depends though on the soil dehydration time and progression.

Causality mapping: Modeling steps are depicted in figure 2.1 (causality mapping overview) referred to as soil system output variables. Input variable of a soil-based irrigation approach is the sensed soil system output variable at time t_0 represented by the output signals for water content (e.g. [l/g]), or water potential (e.g. [hPa]), or a related signal (e.g. [Ω]). The output variables of a model-based irrigation approach

are the irrigation time [h], as well as the volumetric irrigation water quantity to be applied per area [l/m^2]. This quantity equals the negative difference between the soil system output variable at t_1 and the upper target threshold, and it results from water content/water potential changes in the soil system. The conversion of the input term into the output term is basically implemented by (i) the (empirically determined) correlation between soil water potential and soil water content, and (ii) the (empirically determined) conversion of a water fraction term ($[l/g]$ or $[g/g]$) into an area related irrigation quantity in terms of [l/m^2]. The input and output variables of crop models used for irrigation purposes are basically identical to those in model-based irrigation approaches. The conversion instead is not restricted to the soil system, but includes model modules for plant processes and atmosphere processes additionally (cp. following chapters).

2.3.2 Plant system

Boundaries, components: Plant system considerations define the plant's surface as system boundary to the soil (root surface) and to the atmosphere (shoot/leaves surface) [JGG⁺11] [Pas82] [JT98]. Considering whole, individual plants the plant water status is based on a functional subdivision between roots (water uptake), shoot (water transport), and leaves (water transpiration). In the roots water uptake mainly takes place at the meristematic area behind the roots tip, where the roots hair is developed and the root cortex is not yet suberized. In the shoot water is transported (long-distance) primarily in the vascular bundle, from root to leaf in the xylem system, and from leaf to root in the phloem system [Lös01]. At the leaves water is transpiring: Outer layer of leaves (cuticula) prevents the plant from uncontrolled transpiration. Water vapor diffuses from inside the plant almost solely through the stomatal apertures to the surrounding atmosphere. Stomata denote apertures in the cuticula on the lower leaf surface. The degree of stomatal aperture and thereby transpiration rate is regulated by the plant. Transpiration represents water releases of the plant system [JS14] [SBMH02]. The difference between root water uptake and leaves' water transpiration releases in [l] is plant water usage for growth/reproduction. Predominant part of the water uptake by plants is released by transpiration. Crops in the temperate zone use between 150-800kg water for the production of one kg dry matter [Lar01] [Ehl96].

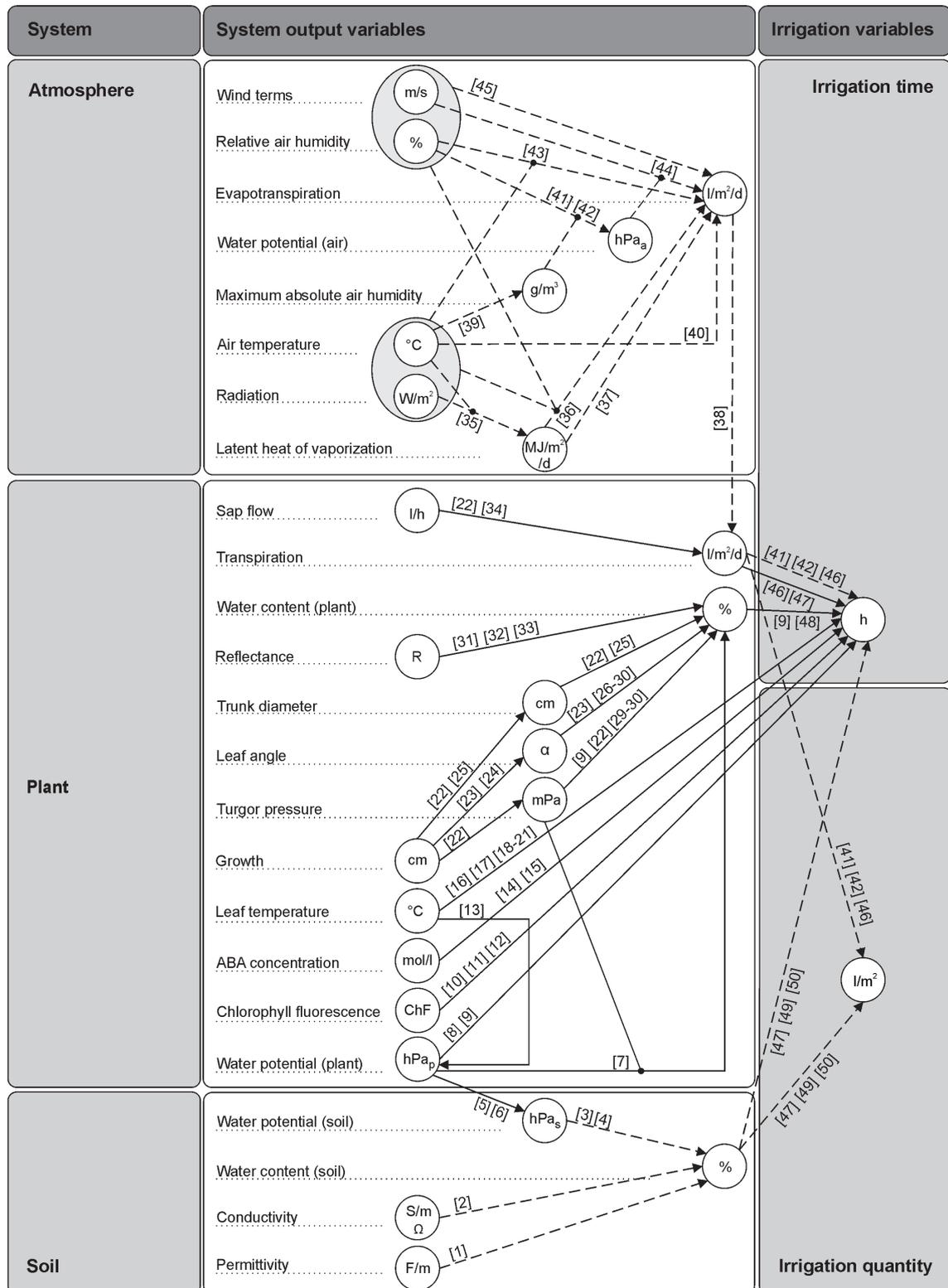


Figure 2.1: Causality mapping overview [KS17]: System-based output variables conversion into irrigation variables of soil-, plant-, and atmosphere-based irrigation approaches. Continuous arrows denote plant-based output-input-relations (including plant dynamic behavior). Dashed arrows denote soil-, or atmosphere-based output-input-relations (without plant dynamic behavior). Numbers on arrows denote bibliographical reference for the relation (cf. table 2.1).

Table 2.1: Bibliographical references causality mapping (figure 2.1) [KS17]

1	[KCB13]	11	[vdTVR09]	21	[Jon99]	31	[BML14]	41	[TE91]
2	[AHMU04]	12	[LZH14]	22	[BTS13]	32	[JBP+10]	42	[vdW73]
3	[ABF+10]	13	[GIK+13]	23	[BGKA+10]	33	[ARR+15]	43	[TM57]
4	[Buc07]	14	[CBE+05]	24	[Bra97]	34	[Fuc90]	44	[PJ14]
5	[WA02]	15	[ZRS+10]	25	[Jon04]	35	[DDM09]	45	[Dal01]
6	[AAC+99]	16	[CBGB91]	26	[MPCA89]	36	[FP13]	46	[Mol93]
7	[RUDB98]	17	[JIRPJ81]	27	[MJR+78]	37	[Cla34]	47	[Rog15]
8	[SBMH02]	18	[IJR78]	28	[Ehl96]	38	[APRS98]	48	[JT98]
9	[Jon07]	19	[MW97]	29	[ZRW+08]	39	[BLID11]	49	[Mas02]
10	[FBMG08]	20	[JKC88]	30	[JS08]	40	[Bur13]	50	[Bay08]

Considering the smallest functional unit in plants, i.e. a cell, the plant cell water status is based on the coaction of the cell wall and the central vacuole, which both are characteristic for plant cells but not for animal cells. The cell wall encloses the protoplast. The protoplast denotes the functional cell unit enclosed by the cell membrane. The cell wall consists of cellulose and pectin, has i.a. protective and structuring function, and serves as filter. Cell walls protect the protoplast from bursting when water diffuses into the protoplast. The central vacuole is an intra-cellular sub-space enclosed by a membrane (tonoplast). It contains cell sap, generates the turgor pressure, and adsorbs water by osmosis for plant growth. Turgor or turgor pressure denotes the mechanical tension of the cell sap on the cell wall. Plant growth is realized in large parts by cell enlargement through cell water uptake rather than by cell division. Growth is defined as irreversible gain in volume. Plant cells gain volume mainly by cell/vacuole water uptake. The cell volume gain is attended by a corresponding strain of the cell walls (hydromechanical system). This plastic strain leads to a stress-relaxation of the cell walls resulting in an irreversible cell wall strain. This process allows a cell growth of up to the 100-fold of the original size [JS14] [Lös01] [Kut95] [SBMH02] [Von71].

Considering a composite of cells on sub-plant level, i.e. plant tissues, the plant tissue water status is based on the coaction of intra-cellular and inter-cellular spaces. Plant tissues consist of symplast and apoplast. Symplast denotes the entirety of the intra-cellular spaces (protoplasts) which are connected by specific channels, the plasmodesmata. Apoplast refers to the inter-cellular space and denotes the entirety of all cell walls and inter-cellular spaces. In the apoplast the resistance to diffusion is low compared to the symplast. It is also referred to as the Apparent Free Space (AFS). At the plant system boundary the apoplast is delimited to the surrounding environment by a water-impermeable covering (cuticula) except at the roots hairs, where the apoplast is open for the ambient aqueous phase. In the roots the Casparian Strip, a particular water-impermeable layer at the internal passage of the plant tissue

to the vascular bundle (xylem, phloem), prevents from a barrier-free water diffusion through the apoplast into the xylem. Water has to enter the symplast in order to pass the Caspary Strip [JS14] [Lös01] [Kut95] [SBMH02].

It can be summarized, that plant system boundary is naturally defined by plants surface (cuticula, apoplast at the roots hairs). On the other hand, plant water status can be studied on different scales: Cell, tissue, or whole plant (or simplified on field scale) as investigated exemplary in [Jon07] [JT98] [MJR⁺78] [MPCA89].

System state, variables, signals: Plant system water state is related to

- water contents (e.g. cell or tissue water content),
- water flows (e.g. sap flow in the xylem), and
- water potentials (gradients) (e.g. water potential differences between tissues) [JT98] [WA02] [BGKA⁺10].

Water content depends on the particular morphology m of the plant species, e.g. leaf succulence [Jon07], and the actual water amount remaining in the plant system, i.e. the water quantity difference between uptake u and release r . As a result, **water status** of a **plant** based on **water content** (wsp-c) can be described by the vector $\mathbf{wsp-c}=[m,u,r]^T$.

Water flow depends on five variables: Water potential gradient g between the considered locations/tissues, the distance d between these locations/tissues, the resistances re and capacitances ca in the path between the locations/tissues [JGG⁺11] [JT98], as well as water uptake u , i.a. ensuring a continuous transpirational pull without cavitations. As a result, **water status** of a **plant** based on **water flows** (wsp-f) can be described by the vector $\mathbf{wsp-f}=[g,d,re,ca,u]^T$.

Water potentials can be considered on sub-plant level and on whole plant level. Water potential on sub-plant level depends on pressure potentials pr , equating to cell-internal pressures on cell walls (turgor), matrix potentials ma due to adhesive forces, and osmotic potentials o caused by concentrations of the solute in vacuoles and tissues [Kut95] [SBMH02]. Osmotic potentials only arise in presence of semi-permeable membranes i.e. not in the vascular bundle [JT98]. Water potentials on whole plant scale additionally depend on gravitational potentials gr antagonizing the transpirational pull [JT98], and water uptake u , resulting in water potential changes in time. As a result, **water status** of a **plant** based on **water potentials** (wsp-p) can be described by the vector $\mathbf{wsp-p}=[pr,ma,o,gr,u]^T$.

Summarizing the listed state variables, the total plant system water status (**wsp-c**, **wsp-f**, and **wsp-p**) can be described by the vector $\mathbf{wsp}=[m,u,r,d,re,ca,pr,ma,o,gr]^T$. Here, the variable g is not listed, as it is represented implicitly by the vector **wsp-p**. The total plant system water status vector **wsp** can be extended if for example plant growth (in time) is considered: Volumetric cell growth is determined by the state variables 'potential cell wall strain' cw , 'membranes water conductivity' mc , 'water potential gradient' g , and 'turgor' pr) [JS14] [Lös01] [Kut95] [SBMH02]. Considering additionally reproductive growth stages (e.g. fructification, ovule) the vector can be further extended by variables determining the apoplastic, symplastic and specific carrier transport systems cs , the assimilate and water storage systems in reproductive organs ro , and plant genotype characteristics pg (sink-source) [CZF⁺10] [SBMH02] [TPCW14] [YS10]. Summarizing the above cited facts, plant system water status is related to a considerable number of state variables on different scales (cell, tissue, whole plant) which are partly interconnected.

Different output variables for plant water status determination for irrigation are given in literature [PKM09] [Jon04] [Jon07] [Fer14]. In [Jon04] two general categories of output variables are distinguished:

- Plant water state-based (a), and
- plant physiological response-based variables (b).

In category (a) output variables express the actual plant tissue water content or related values. Output variables of this category assume the observability of the plant water state by the current plant water content or related variables. Output variables of category (a) are:

- Amount-based variables like the Relative Water Content (RWC): The RWC represents the normalized water content of a plant tissue. The RWC is defined as the actual water content related to the potential water content at full turgor in [%] [Jon07] [JT98].
- Energy-based variables like the plant water potential: Similar to a.m. soil water potential, the plant water potential is defined on a thermodynamic basis in consideration of the chemical potential of water and its partial molal volume [Jon07]. The plant water potential is expressed in pressure units e.g. [mPa] [JS14] [SBMH02] [Jon07].
- Water content related values like turgor pressure: The turgor pressure represents the hydrostatic intracellular pressure on the cell wall. Cell water content and turgor pressure are related values. The turgor is involved in physiological

processes of cell growth, gas exchange, and transportation and is for herbaceous plants responsible for the mechanical stability and rigidity [JS14] [Lös01] [SBMH02]. Turgor pressure is expressed in

- pressure units e.g. [mPa] [Fer14] [BEZ⁺13] [ZRW⁺08], or in
- extent units like leaf thickness or trunk diameters [cm] [Jon04] [Fer14], or in
- angle units representing visible wilting symptoms because of reduced turgor pressures [MPCA89] [JS08].

The measured output signal for variables of category (a) is compared with a (experimentally determined) threshold value (e.g. the output signal of well watered comparative plants) in order to trigger irrigation events.

In category (b) output variables express the actual emission/output caused by a physiological/physical process which is known/assumed to be affected by a water deficit experienced by the plant. Output variables of this category assume the observability of the plant water state by the output variable of the respective physiological process. The value of the measured output signal is as well compared with a threshold value to trigger irrigation events. Output variables of category (b) comprise emissions/outputs of:

- Stomatal conductance (SC): The SC represents the quantity of gas exchange of leaves with its surrounding atmosphere via the stomata. It is defined as the quotient of transpiration the water vapor pressure difference (i.e. water potential gradient) between leaf and atmosphere [JS14] [SBMH02]. The quantity of transpiration through stomata varies in time i.a. depending on stomatal aperture. This stomatal aperture is regulated by the plant, i.a. induced by water deficits [CLL⁺09] [Bra97] [DSCU10]. Output variables for stomatal conductance are:
 - Stomatal conductance directly measured e.g. with a porometer: Stomatal conductance is expressed in [mmol/m²/s] [SC15].
 - Transpiration: The transpiration denotes '*the vaporization of liquid water contained in plant tissues and the vapour removal to the atmosphere*' [APRS98]. Output variables for transpiration are expressed e.g. in [l/m²/d] [CBGB91] [APRS98].
 - Leaf temperature: Transpiration at the leaf surface through stomata generates evaporative cooling. Altered stomatal apertures result in changing leaf surface temperatures caused by varying evaporative cooling. Leaf temperature is expressed e.g. in [°C] [JIRPJ81] [Jac82] [Fuc90].

- Sap flow: The sap flow represents the vertical antrorse water movement in the xylem system mainly caused by the transpirational pull [JS14] [Lös01] [SBMH02]. Altered stomatal apertures result in changing transpiration rates and hence in changing sap flow rates. Sap flow is expressed e.g. in [l/h] [Fer14] [CBE⁺05].
- Growth rate: Growth is defined as irreversible volume increase in time. Turgor pressure is a major factor for plant growth because of the plant specific, hydraulic cell growth process [JS14] [Lös01] [SBMH02]. Changes in plant water state, particularly in turgor pressure, result in variations of growth rates. Growth rate is expressed in lengths for e.g. leaf elongation or fruit/trunk diameters [cm] [Jon04] [Fer14].
- ABA produktion: Abscisic acid (ABA) is a growth regulator produced by the roots exposed to a water deficit. A rising concentration of ABA in the xylem sap induces i.a. the closure of the stomata leading to reduced transpiration [JS14] [Tar96] [LSZ⁺08]. The ABA concentration is expressed in [mol/l] or [nM] [Asc00] [FBMG08].
- Chlorophyll fluorescence: Photosynthesis is defined as the transformation of light energy into chemical energy and subsequently the transformation of low-energy substances into high-energy ones [JS14] [SBMH02]. The process of photosynthesis is affected by the plant water state [CPM⁺02] [SBMH02] [vdTVR09]. The disruptive effect of a water deficit on the photosynthesis process is observable by changes in the leaves' chlorophyll fluorescence course at photosynthesis induction (Kautzky effect [KH31]). Chlorophyll fluorescence is expressed by the value/course of characteristic chlorophyll fluorescence intensities (origination, terminal, and key inflection points) and is denoted in Fluorescence Units [FU] [LZH14] [BML14].
- Reflectance: Reflectance denotes the portion of light/radiation spectrum reflected by a leaf or canopy. Water deficits result in changes of radiation reflectance at the wavelengths above the visible spectrum (more than 700nm) i.e. at the infrared spectrum. Reflectance is utilized to estimate the leaf/canopy water content and is expressed in Reflectance [R], the portion of reflected radiation at incident radiation [LZH14] [PFB⁺93] [PF98] [CvdS00].

Processes, dynamics: The movement of water into and through the plant can be roughly described as follows [JS14] [Lös01] [Kut95] [SBMH02] [Von71] [Ehl96]: Water uptake (soil to root) is mainly driven by diffusion according to an osmotic pressure gradient caused by assimilate concentration in the roots. Water transport from root surface into roots radially to the roots axis/central cylinder takes place in the root tissue. Generally, two different transportation paths for water in plant tissues are known: The apoplastic transport, and the symplastic transport [Lös01] [SBMH02].

The apoplastic transport takes place in the Apparent Free Space (AFS). In the apoplast the resistance to diffusion is low compared to the symplast, but this transportation path is limited in the roots by a water impermeable layer (casparys strip) around the central cylinder. This layer prevents water uptake from the apoplast directly into the roots central cylinder and for further (long distance) transport in the vascular bundle. Water from the apoplast has to enter the symplast in order to be uptaken and transported via the xylem. Instead, the symplastic transport takes place in the intra-cellular space and through the plasmodesmata. Water from the symplast is uptaken directly into the roots central cylinder and available for transportation in the xylem system. The water uptake into individual cells and the central vacuole is also driven by osmosis [Lös01] [SBMH02]. If the osmotic value within the cell/vacuole is higher than in the cell surrounding apoplast water diffuses into the cell/central vacuole. Water transport (long distance) from root to leaf via the xylem (sap flow) continues along a water potential gradient. This gradient is predominantly produced by the transpirational pull because of transpiration at the leaves surface. Additionally, roots are able to produce an osmotic root pressure pushing the sap flow upwards. This roots pull may produce pressures of up to 6 bar (0.6 mPa) and being kept even if the transpirational pull is interrupted e.g. because of stomatal closure. Water releases by transpiration (leaf to atmosphere) result from water diffusion through apertures in the lower leaf surface (stomata) alongside the vapor pressure gradient between leaf and atmosphere. Water transport from leaf to root via the phloem, responsible e.g. for the transport of assimilates into roots, again continues along an osmotic pressure gradient caused by assimilate concentration differences in plant tissues [JS14] [Lös01] [Kut95] [SBMH02] [Von71]. Thus, driving forces for water movements in plants are mainly water potential gradients and osmotic pressure gradients.

The dynamics (emergence and changes) of water potential and osmotic pressure gradients on whole plant scale (water uptake, long distance transport, and water release) are mainly induced by changes in soil water potential (cp. chapter soil system) and in water potential of the relevant, surrounding atmosphere (cp. chapter atmosphere system). As soil water potential drops due to reduced soil water content, plant roots reduce root water potential accordingly, hence though still extracting water from the soil. Correspondingly, as atmosphere water potential drops due to e.g. reduced air humidity or increased temperature, plant leaves reduce transpiration area (i.e. closure of stomata) preventing the plant from uncontrolled excessive transpiration, and hence water releases [JS14] [Lös01] [SBMH02]. Related to water deficits, the dynamics of water potential and osmotic pressure gradients on plant tissue or cell scale is mainly induced by the detection of a water deficit by the plant; the plant internal physiological detection processes are not fully explained yet [CZF⁺10] [Bra97]. Water deficit to plants occurs when transpiration losses rise above water uptake, either by restricted water supply or by increased

water loss [Bra97]. Water deficits tend to reduce crop productivity. Water deficits experienced by plants cause protoplast volume reductions, concentration of cell sap, turgor reduction, and changes in transmembrane potential gradients [SBMH02]. This impacts several physiological processes in plants, e.g. root and leaf development, photosynthesis, flowering, and development rates [JS14] [Lar87] [CPM⁺02] [McM08], albeit in different sensitivities [Lös01] [Hsi73] [Jon04]. Short-term responses of plants to water deficits aiming at improved water uptake are for example osmotic adjustments or an increase of cell wall expansibility in root cells [WC00] [DKLJ10]. Short-term responses of plants to water deficits aiming at reduced water releases are for example shoot growth inhibition or stomatal closure caused by root signalling [Lös01] [SBMH02]. Long-term responses of plants to water deficits are for example sustained root growth or reduced transpiration area by early leaf senescence [CPM⁺02] [CMP03]. Major driving force in whole plant drought responses is signalling by abscisic acid (ABA), a growth regulator produced by the roots under water stress and influencing manifold biochemical and physiological processes as well as growth, flowering, and morphology [JS14]. Generally, the type and scale of drought responses depend on species, time and dimension of water losses, developmental stage, as well as on organ/cellular characteristics [Bra97]. Additionally, in [TGM11] 'feedback' effects between individual responses are assumed to exist. Here, 'feedback' is described as an open-loop feedback thus representing rather an interaction between processes than a feedback in a narrower sense of control taxonomy. To this effect a coordination network for three major water deficit induced processes, namely carbon (biomass) accumulation, cell number, and tissue expansion, is introduced. The authors assume the three processes being strongly selfconnected but only slightly interconnected by interaction effects. For example, an interaction effect is mentioned for C-metabolism on expansive growth, or for cell division and tissue expansion. Ultimately, the proposed network is opposed to two other coordination options between these processes: The first highlighting carbon availability dominating the other processes, and the second describing all processes as parallel and not interacting at all.

Concluding it can be stated that water-related states and processes in plants are influenced by water contents, water flows, and water potentials. Plant responses to water deficits are either aiming at improved water uptake by the roots, or at reduced water releases, or at improved/more efficient water use. Actual plant responses to water deficits depend on plant specific parameters (species, cultivar, individual plant, developmental stage), and on the water deficit severity (time and dimension). Interactions between physiological processes are assumed to exist.

Models: Basic idea to employ plant system-based models for irrigation purposes is to irrigate based on actual plant water status [PKM09] [Jon04] [Fer14]. Here, plant system output variables are modeled to determine time/quantity of irrigation events.

Plant system-based models can be roughly distinguished into

- plant water balance-based models (a) [RYS⁺00], and
- plant water status-based models (b) [Jon04].

In plant water balance-based models (a) the water status of a crop is assessed by balancing plant water uptake with plant water release. Results deviating from experimentally determined threshold values trigger irrigation events. For example, in [GVFM⁺09] and [GRG10] the crop model AquaCrop [SRH⁺09] was used for the development of Deficit Irrigation (DI) schedules for cotton and quinoa. In AquaCrop the crop yield is related to crop water use (equal to water uptake minus water release) by crop specific, linear water production functions. These functions reflect the disruptive effect of water deficits on yields considering species and developmental stages [SHFR12]. In [GRG10] seasonal/irrigation event-based crop water requirements for water sensitive growth stages of quinoa are calculated. The derived irrigation schedule was developed in four steps: (1) Simulation of sensitive growth stages under rainfed conditions. (2) Detection of quantitative thresholds for developmental stages signalling the start of water deficit sensitive stages. (3) Simulation of several growing seasons under different irrigation schedules. Irrigation quantity is given for each case as a fixed partial dose sufficient to refill soil water content up to the defined, soil specific threshold serving as irrigation time trigger. (4) Simulated results are converted into DI irrigation schedules with varying irrigation intervals for sensitive developmental stages. As another example, in [HCB13] and [Hoo94] the crop model CERES [RUDB98] was used for the development of irrigation schedules for wheat and maize. In CERES the crop yield is related to crop water use. The disruptive effect of water deficits is introduced by two yield-reducing factors reflecting developmental dysfunction at a mild and at a more severe water deficit. At a mild water deficit defined as threshold of soil water depletion the factor TURFAC is activated, representing reductions in expansive growth. The factor TURFAC denotes the quotient of the potential root water uptake (soil water availability) to the potential transpiration (plant water release) weighted by a constant crop specific factor. The value of the factor TURFAC lies between 0 and 1, and its function is proportional to the named quotient. If TURFAC drops below a threshold, the simulated yield is reduced (TURFAC below 1). Further, as soon as potential transpiration equals or exceeds potential root water uptake a second factor is activated: SWFAC. This factor represents reductions in further developmental processes like biomass accumulation or flowering. The factor SWFAC as well denotes the quotient of the potential root water uptake to the potential transpiration, but it is activated at a lower quotient value than TURFAC. The SWFAC function is as well proportional but with a higher gradient than of TURFAC [HCB13].

In plant water status-based models (b) the water status of a plant is derived from measured crop water output variables serving as input variables for irrigation scheduling. Different options for the conversion of plant system-based output variables into irrigation input variables (time and quantity) are described in literature:

- First: Measurement of plant (tissue) water state output variables and the deduction of irrigation input variables: In [VG88] the relations between leaf turgor, relative water content (RWC), and leaf water potential (LWP) exemplary for potato leaves are investigated with regard to genotype selection. In potatoes with full irrigation a leaf water potential of $-1,0\text{MPa}$ and a turgor pressure of $0,1\text{MPa}$ were measured. A turgor loss due to a water deficit was measured at a relative water content of $0,92$ and a leaf water potential of $-0,8\text{MPa}$. Results of comparable studies for other plant species (alfalfa, field bean, sunflower, wheat) are also noted: Turgor pressure (full turgidity) is ranging for all crops between $0,7\text{MPa}$ and $1,2\text{MPa}$; the points of turgor loss are given between RWC of $0,95$ and LWP of $-1,3\text{MPa}$ (alfalfa) and RWC of $0,76$ and LWP of $-1,1\text{MPa}$ (field bean). In wheat a LWP of up to $-1,4\text{MPa}$ was measured. Hence, water relations differ significantly between species requiring plant specific thresholds for irrigation purposes. In [GMdC⁺06] for example the threshold for irrigation time of vine based on leaf water potential measurements is introduced. In a three years experiment three different irrigation treatments (full irrigation (FI), mild deficit irrigation (MD), severe deficit irrigation (SD)) were defined by setting rising leaf water potential thresholds at $-0,6\text{MPa}$ to $-0,8\text{MPa}$ (FI), $-0,6(\text{MPa})$ to $-1,2\text{MPa}$ (MD), and $-1,0\text{MPa}$ to $-1,2\text{MPa}$ (SD). Results show yield quantity reductions compared to FI treatments of about 20 percent for MD (increasing over three years), and of about 50 percent for SD. Yield quality in MD-treatments was superior to both other treatments. The irrigation input variables are set for irrigation time at the named thresholds, and irrigation quantities are numbered with average annual irrigation amounts of 374mm/a (FI), 250mm/a (MD), and 178mm/a (SD). In [ZRS⁺10] turgor pressures of banana leaves were measured to investigate relations between plant water status and leaf turgor pressure behavior. Variables for the detection of an incipient water deficit (threshold for irrigation timing) are proposed to be (a) the amplitude of the leaf turgor peak at noon, and (b) the oscillation of the measured pressure signal which is solely measurable at well watered plants (cell turgor below 100kPa), but decreases under water deficit. Irrigation quantities are not discussed with regard to irrigation thresholds.
- Second: Comparative measurement of plant-based variables and soil-based variables: Known soil-based thresholds are used for the determination of related plant-based thresholds. In [LSZ⁺08] [JBP⁺10] for example the threshold for an optimal xylem ABA-concentration for irrigation changeover in Partial Rootzone Drying (PRD) for potatoes is given with 150nM compared to 115nM in fully

irrigated plants. This threshold for the irrigation input variable 'irrigation time' was determined experimentally by measuring xylem ABA-concentrations compared to soil water potential signals at different soil depletion stages. Under the presented experimental conditions a 150nM ABA-concentration equals a soil water potential of about -80kPa. The irrigation input variable 'water quantity' was fixed at 18 percent of volumetric soil water content but not determined based on plant-based variables.

- Third: Comparative measurement of different plant-based variables: Known plant (tissue) water state output variable thresholds (e.g. leaf water potential) are used for the determination of unknown related plant-based thresholds. In [PFB⁺93] for example water stress indices for gerbera plants based on three reflectance indicators were developed: (i) Reflectance at 950nm (a water absorption band) related to a reference reflection at 900nm (R_{970}/R_{900}), (ii) the first derivative minimum in this near-infrared spectrum, and (iii) the wavelength in which this derivative minimum occurs. Comparative measurements were made for Relative Water Content (RWC), leaf water potential, stomatal conductance, and foliage-air temperature. The indices correlate significantly with the selected plant water state output variables; particularly at RWC values lower than 85 percent, corresponding to a stomatal conductances of 0,075 mmol/m²/s, and -1,5MPa leaf water potentials. The conversion into irrigation input variables (time and quantity) was not quantified in this study. The identification of reflectance-based thresholds for irrigation is relevant in the context of other investigations, e.g. for cotton [ARR⁺15], or sweet corn [GIK⁺13]. As another example, in [CAM⁺05] the leaf water potential and canopy temperature of cotton were comparatively measured. Here, leaf water potential is considered to reflect plant water status, and leaf temperatures were measured and processed to reflect spatial leaf water potential distribution in the field. The conversion into irrigation input variables in terms of quantitative thresholds is not specified in the study.
- Fourth: Measurement of a plant-based variable and model-based conversion into an index serving as irrigation input variable: An example for this approach is the stress-degree-day concept introduced in [IJR78]. Here, a modification of the growth-degree-day concept describing crop development based on daily cumulative air temperatures is proposed [MW97]. A stress-degree-day denotes the 'crop canopy temperature' minus 'air temperature' differential and describes developmental delays due to water stress. The approach was further developed to the Crop Water Stress Index (CWSI) concept as described in [JKC88] based on canopy temperature values only. In [Jon99] the index was refined by replacing the theoretically estimated reference temperature of leaves from well-watered plants by measured wet and dry reference surfaces and introducing an index being proportional to stomatal conductance (and hence stomatal

aperture). According to [WY16] irrigation e.g. in soyabean is usually triggered at a CWSI of above 0,24.

With regard to plant system-based models it can be summarized that:

1. The input variables for irrigation scheduling (time and quantity) can be derived either by balancing soil water content with plant and soil water releases, or by deriving the irrigation input variables from sensed plant based water status variables.
2. In crop models the dynamic behavior of plants being exposed to planned water deficits can be reflected by introducing different irrigation treatments for different developmental stages. In crop model AquaCrop for example the crop specific water production function for DI is composed of segments of the different, linear, developmental stage-related production functions.
3. The conversion of a plant-based water status output variable into an irrigation input variable can be either implemented directly by measured or modeled plant-based thresholds, or indirectly by the comparison of plant measurements with known thresholds of other plant- or soil-based output variables.
4. All investigated studies describing plant water status-based models referred to the irrigation input variable 'irrigation time' denoted as sensed incipient crop water stress.
5. No study could be found focussing on the quantification of a threshold for the irrigation input factor 'water quantity' on the basis of plant-based signals only, although quantitative irrigation treatments were (partly) described. The latter conclusion is similarly drawn in [Jon04] [Jon07] [WA02].

Input variables for plant water balance models are:

- Initial plant water status term: Time period in crop models is usually the plants lifecycle from sowing till harvest. This determines the point in time for the initial status determination at the time of sowing. Accordingly, in [GRG10] and [HCB13] the actual plant water status is derived by the definition of an initial soil water content at sowing. Here, the initial plant water status is fixed as being 'fully irrigated' at a soil field capacity of about 70 percent.
- Plant water uptake term: Plant water uptake depends on soil water availability (cp. chapter soil system) and on the plant specific root water uptake ability. The plants ability to extract water from the soil depends on its root and physiological characteristics as well as on atmospheric conditions (e.g. air temperature) [JS14]

[SBMH02]. Water uptake is modeled either directly using a model for root water uptake, like in crop model CERES-wheat, or indirectly by equating water uptake with transpiration losses, like in APSIM crop model. The latter concept assumes similar water quantities for water uptake and transpiration omitting explicit water uptake models. Root water uptake can be modeled either in a microscopic approach, or in a macroscopic approach [GKC06] [KSJ14]. In the microscopic approach root-water uptake is determined based on "*microscale physics of water flow from the soil to, and through, the plants roots*". The model consists of a conductivity term, the water pressure head gradient soil-root, and a water flow geometry term [GKC06]. According to [Dee08] microscopic approaches are used e.g. in crop models like CERES-wheat [Rit85], APSIM-SWIM [KCH⁺03] [HBV12], or CROPGRO-soybean [BJHP98]. Alternatively, in a macroscopic approach the root-water uptake term is extracted from empirical functions describing plant reaction to water potential [GKC06]. The actual root water uptake is modeled by multiplying a maximum root water uptake value by the dimensionless, empirically determined stress response function. For example in the crop model AquaCrop [SRH⁺09] the water extraction patterns are predetermined at 40 to 10 percent for every quarter of the effective rooting depth [SRH⁺09].

- Plant water release term: Plant water releases are primarily due to transpiration at the plants leaves. Water transpiration is determined by the evaporative conditions like air temperature, vapor pressure deficit, radiation, or wind speed [RBGRA14] [APRS98] (cp. chapter atmosphere system). Transpiration represents the water outflow in a plant water balance consideration. In crop models transpiration is considered either by equating transpiration to water uptake (e.g. in crop model DAISY [AH00]), or by introducing a transpiration coefficient adjusting this water uptake to certain plant- and atmospheric conditions (e.g. in crop model APSIM [KCH⁺03]). Alternatively, transpiration is computed as a share of total evapotranspiration (ET), whereas it is necessary to distinguish between transpiration (plant) and evaporation (soil) [APRS98].

Input variables for plant water status-based models for irrigation are the above described plant water status output variables. Measured plant water status output variables are modeled to derive indices (e.g. the above mentioned CWSI or reflectance index) indicating a plant water stress state. If an index threshold is reached, irrigation is triggered.

It can be derived from the above cited facts, that irrigation based on plant water balance approaches (crop models) considers plant dynamic behavior by introducing linear yield reduction functions. These approaches determine irrigation input variables (quantities and timing) either based on the soil water status (assuring sufficient

water supply) [GRG10] [HCB13], or based on evaporative plant water releases (as an indicator for water consumption) [APRS98] [PT14] [STSH07] [PP11] (cp. chapter atmosphere system). Irrigation based on plant water status-based approaches considers plant dynamic behavior by introducing empirically defined thresholds triggering irrigation at the point of water stress incipience. Here, irrigation water quantity (actual plant water demand) is determined using soil- or atmosphere-based methods.

Causality mapping: Modeling steps are depicted in figure 2.1 (causality mapping overview) referred to as plant system output variables. Input variable of a plant-based irrigation approach is the sensed plant system output variable (considered at a certain time t_0) represented by the output signal for (i) plant tissue water content [%] or related values (e.g. [cm]), alternatively for (ii) the emission/output caused by a physiological/physical process (e.g. [l/h]). To date, output variable of plant-based irrigation approaches is solely the irrigation time [h]. Here, conversion of the input terms into the output term [h] is basically implemented by the derivation of a threshold value for (i) plant tissue water content [%], or (ii) plant system water transpiration (release) [$\text{mmol}/\text{m}^2/\text{s}$], or (iii) individual, empirically determined and process-related indices (e.g. CWSI). Irrigation is triggered if the specific threshold is reached by the sensed/modeled plant system output variable. Determination of the volumetric irrigation water quantity to be applied per area [l/m^2] based solely on plant-related output variables is not yet realized. In crop models used for irrigation purposes dynamic plant behavior is introduced by yield reduction functions. Here, irrigation time and quantity determination is based on soil and atmosphere considerations.

2.3.3 Atmosphere system

Boundaries, components: As atmosphere the gaseous mixture of the earth atmosphere is denoted. The atmosphere consists of principle components nitrogen (78 volume percent), oxygen (20 volume percent), and argon (1 volume percent) [Möl03]. Additionally, at ground level the atmosphere contains in average 1.3 volume percent water vapor (below one percent at the poles, up to three percent in the tropics) [Möl03] [WE12]. Water vapor is about 40 percent lighter than air hence ascending to higher atmosphere layers until the water condenses. Above this condensation layer water vapor content of the air is considerably lower than at ground level. Average water vapor content of the total atmosphere is about 0.4 volume percent [Möl03] [WE12].

As an atmosphere system a certain spatial portion of the atmosphere enclosing the plant assumed to have influence on water related processes of crops, particularly on the evapotranspiration of water (plant water releases), is denoted. Evapotranspiration

(ET) comprises water evaporation resulting from two sources: (i) Transpiration (T) of water from inside the leaves (water releases of plants) and (ii) evaporation (E) of water from plant external surfaces (e.g. soil, water drops on leaves) [APRS98]. Both processes denote the phase transition of water from liquid to gaseous [Möl03] [WE12]. Evaporation and transpiration are mostly considered jointly as ET because the extraction of the plant's transpiration share of the measured or modeled ET-value is not readily possible [JS14]. Additionally, a characteristic change of ET behavior with respect to a slow time scale is known: At early developmental crop stages evaporation from the soil makes up a high share in ET, at full canopy crop stages transpiration is dominant [APRS98].

Lower boundaries of the atmosphere system to the plant as well as to the soil system are naturally defined by the plant's and soil surface [BGJ⁺03]. The boundary of the ET-relevant atmosphere to the residual atmosphere is defined differently in literature: In [BGJ⁺03] the system boundaries are defined: *"The upper boundary of the system is the atmosphere characterized by standard climatic variables (radiation, minimum and maximum temperatures, rainfall, reference evapotranspiration and possibly wind and humidity) and the lower boundary corresponds to the soil/subsoil interface."* In [APRS98] the measurement of atmospheric parameters at standardized heights of 2 m above ground (for wind speed, temperature, and humidity) at an assumed crop height of 0.12 m is stated for the determination of the ET of a grass reference surface. In [SJ05] atmospheric parameters for ET calculations are measured between 0.14 m (pan evaporation) and 3.3 m (wind speed). In [Shu08] heights of *"a few meters above vegetation"* are mentioned for the parameter measurement of water vapor transfer methods. Finally, in [GFP⁺15] parameters are measured at heights between 0.57 m (gas analyzer) and 2.6 m (wind components sensor). Summarizing, the upper boundary of atmosphere systems is not consistently defined. In [APHJ11] best practice recommendations for standardized ET data acquisition are given.

System state, variables, signals: Atmosphere system water state for irrigation purposes is related to

- air water vapor content, and
- air water potential [APRS98] [Möl03] [WE12] [DVW96].

Air water vapor content depends particularly on air temperature *at*: Maximum air humidity (water vapor saturation) denotes the water quantity that one m^3 air can absorb at most. At air temperature of e.g. 20°C the volume of one m^3 air can absorb about 14g water, at air temperature of 30°C about 30g water, and at 60°C about 100g water (at atmospheric normal pressure) [Möl03] [WE12] [G11]. Additionally, air water vapor content is determined by water vapor intakes (by evaporation) *ev*

and releases (by condensation) *co*. Evaporation denotes the phase transformation of water from liquid to gaseous, condensation denotes the inverted phase transformation from gaseous to liquid state [Möl03] [WE12]. As a result, **water state** of the atmosphere based on water vapor content (*wsa-c*) can be described by the vector $\mathbf{wsa-c}=[at, ev, co]^T$.

Air water potential denotes the vapor pressure difference between air and plant at a time instance [Tar96] [TE91]. This gradient determines plant water releases by transpiration. Physically, the quantity of plant water transpiration in time depends on four variables [Möl03] [WE12] [D VW96]:

- Actual vapor pressure difference between the liquid water surface (in stomata) and enclosing air: Vapor pressure difference depends on the relative air humidity *ah* [vdW73] [Cla34]: The transfer of water molecules from liquid to gaseous phase is proportional to the relative air humidity [vdW73] [Cla34]. The latter denotes the actual air water vapor content related to the maximum possible air water vapor content at the particular temperature [Möl03] [WE12].
- Energy available for the evaporation process at the water surface: The available energy for evaporation depends mainly on the meteorological factors radiation *ra*, and air temperature *at* [APRS98].
- Quantity of evaporated water removed by the air (e.g. by wind): The quantity of removed evaporated water depends on wind terms *wt* [APRS98].
- Liquid water quantity available for evaporation: Liquid plant water available for transpiration depends on soil water availability and precipitation *swp*, and on plant characteristics *pc* (cp. chapter plant system).

As a result, **water status** of the atmosphere based on air water potential (*wsa-p*) can be described by the vector $\mathbf{wsa-p}=[ah, ra, at, wt, swp, pc]^T$.

Output variables for atmosphere water status determination for irrigation refer either to ET-quantity, or to the share of actual plant-transpiration from a maximum possible or targeted ET-value [FS07] [APHJ11] [DDM09]. Output variables determining evapotranspiration quantity approximate the absolute water quantity transpired by the plants which should be replaced by irrigation [KMD⁺16]. Output variables of this category are expressed in terms of depth [mm/d], volume [m^3 /ha/d], or energy [MJ/ m^2 /d], where 1 mm/d denotes 10 m^3 /ha/d or 2.45 MJ/ha/d. Here, energy denotes the latent heat of vaporization denoting the energy required to vaporize free water [APRS98] [Dat11] [Bow26]. Output variables determining the share of actual plant-transpiration from a maximum possible or targeted ET-value describe

by approximation the actual plant water release related to a water release under non-limited water conditions in [%] [APRS98] [KP09]. The determined deviation from a threshold value triggers irrigation time and quantity [DDM09] [How96]. Irrigation quantity can be derived directly from the ET-value expressed in terms of water volume per area and time.

According to [APRS98] different perspectives to ET should be considered (to repeat [APRS98]):

- Reference ET (ET_o) describes the ET of a reference plant surface defined by fixed, standardized plant and soil parameters. This ET_o denotes the climatic evaporative conditions of a non water-limited specific location at a certain time of the year. This approach aims at the comparison of evaporative conditions between different locations and seasons. Average ET_o values e.g. for temperate regions with humid to sub-humid climate range between 1 - 2 mm/d at minus 10°C, and 4 - 7 mm/d at 30°C.
- Standardized crop evapotranspiration (ET_c) denotes the ET of a certain crop grown under non water-, disease-, or nutrition-limiting conditions in a certain location and time. This ET_c denotes the crop specific water release and its value represents approximatively the water quantity to be refilled by irrigation (or precipitation). The ratios of ET_o/ET_c for different crops have been experimentally determined and are expressed in crop specific dimensionless coefficients K_c . For irrigation purposes the ET_c can be determined by multiplying a known ET_o with the relevant K_c [KMD⁺16]. The K_c -value for e.g. cereals ranges between 0.3 and 1.2 depending on developmental stage.
- Crop evaporation under restricted conditions (e.g. water shortage) (ET_{c-adj}) denotes the ET_c of a certain crop grown under limited growing conditions. The ET_{c-adj} may deviate from the corresponding ET_c . These growth limiting conditions can be introduced by stress factors reducing ET_c by an empirically determined portion.

Processes/dynamics: Water vapor and liquid water are linked by mass and energy transfer (evaporation and condensation) [Möl03] [WE12]. Mass transfer denotes the net movement of mass (water molecules) between the phases (liquid/gaseous). The related energy transfer denotes the energy flow interconnected to the mass transfer in the same direction, i.e. the mass energy transfer analogy [BLID11]. Evaporative cooling represents an example for this process: When water evaporates at the surface of liquid water, the water molecules leave the liquid texture to the gaseous phase (mass transfer) subducting also the mass related energy from the liquid phase (energy transfer). The energy removed from the liquid water results in a reduced water temperature (evaporative cooling). The energy used for this phase transition is

denoted as latent heat of vaporization [Dat11]. Molecules of the liquid phase must have a kinetic energy exceeding the water surface binding energy to leave the liquid phase. Energy inputs to the liquid phase e.g. through solar radiation result in increased kinetic energy of water molecules. Hence, more water molecules are able to leave the liquid phase [BLID11] [WE12].

The dynamics of water phase transformation is influenced by a number of variables [RBGRA14] [Möl03] [WE12] [Pen48]:

- Water surface dimension and shape, denoting mainly stomatal aperture size and the concave shape of water meniscus surfaces at the top of capillary vessels. Stomatal aperture size determines the number of water molecules per stomata being exposed to evaporative conditions (the smaller the apertures, the less evaporative surface). A concave shape of water surfaces results in more strongly bonded water molecules to the water surface [Tho72].
- Plant's biological features, influencing this transpiration dynamic by number, size, position, and time behavior of stomata [Lös01] [Hsi73] [Lar01] [DSCU10].
- Air temperature, denoting meteorologically the measured atmospheric temperature at about 2m height from the ground [Möl03] [WE12]. At this height the air temperature is assumed not to be influenced by radiation and soil heat. Air temperature is influencing the number of water molecules having enough kinetic energy to leave the liquid water texture and hence evaporation rate. Rising air temperatures at constant environmental conditions result in exponentially rising maximum water vapor saturation of the air [Möl03] [WE12]. According to Mollier [Mol93] this relation is depicted in h,x- (or t,x-) diagrams. Air temperature in vicinity of the stomata is again influenced by the water temperature, solar irradiation, and wind speed.
- Water temperature, cooling down the air temperature in immediate vicinity of the liquid water surface in stomata if water temperature is below air temperature. This reduces the maximum air humidity in this area and hence the local vapor pressure deficit, i.e the water evaporation rate. Additionally, lower water temperature results in lower average velocities of the liquid water molecules leading to a smaller portion of molecules being able to leave the liquid water texture (evaporation) [Möl03] [Kad06].
- Solar irradiation, increasing the kinetic energy of water molecules. This results in an increase of water evaporation rate. On the other hand, evaporation of water results in evaporative cooling [SJ05] [PJ14]. Hence, the effect of an increased evaporation rate due to a rise in air temperature and irradiation is opposed to the effect of reduced evaporation rate due to a simultaneous cooling effect caused by evaporation and a water-air-temperature difference.

- Wind terms (speed, turbulence), influencing evaporation by removal of water saturated air and the delivery of air of lower humidity [Kad06].
- Water vapor saturation of the air, determining the water potential differences between plant and atmosphere. At 25°C and about 50 percent relative air humidity the atmosphere has a water potential of about -95 MPa compared to -0.5 to -2.5 MPa in leaves (or -0.1 MPa in moist soils). This difference results in a high transpirational pull [Lös01] [Kut95] [Möl03].
- Atmospheric pressure, influencing only marginally the mass transfer under normal atmospheric conditions of about 0.5 percent under different pressures and temperatures [Möl03] [WE12] [G11].

Summarizing, evaporation rate and hence plant water release is determined by the number of water molecules available and being exposed to evaporative conditions, as well as the energy disposable for water molecules to leave the liquid textures. The major atmosphere-based factors influencing ET and hence the dynamic of transpiration are: Solar irradiation and ambient air temperature providing the energy for the evaporative process, as well as air humidity and wind speed determining the water vapor intake capacity of the surrounding air.

Models: Basic idea to employ atmosphere system-based models for irrigation purposes is to model irrigation based on the actual plant water release [Rog15] [DDM09] [AR07]. Here, atmosphere system output variables are modeled to determine time and/or quantity of irrigation events. Irrigation is triggered as soon as a targeted ET_c -threshold value is reached. Irrigation quantity can be derived directly by the ET_c -value in terms of water volume per area and time [KMD⁺16] [KP09] [AR07].

In the reviews [APHJ11] [SC15] evaluations and best practice recommendations are given on measuring/modeling setups including methods

- deriving ET_c by sensing soil water inflows and outflows for soil water balance- and related ET-considerations (cp. chapter 2.3.1),
- determining plant transpiration e.g. by measuring plant sap flow as an indicator for transpirational pull (cp. chapter 2.3.2), or
- modeling ET_c by measuring weather and/or canopy data and using energy or thermodynamic models.

The latter approach includes:

- Empirical methods like the Dalton equation [Dal01] modeling evaporation in [mm/d] on an aerodynamic basis as a function of an empirical factor considering wind speed in [m/s], and the water vapor saturation deficit in [mPa] [ABF⁺10]. Alternatively, the Eddy covariance method [Bur13] [BHM88] is applicable to model vertical turbulent fluxes to estimate ET. Other examples are the approach of Thornthwaite [Tho48] which is based on the empirical relation between ET and air temperature [XS01], or the approach of Turc [Tur61] which is based on the empirical relations between ET and air temperature, global radiation, and air humidity [FP13].
- Energy balance methods modeling ET_c based on the assumption that the sum of all positive and negative energy fluxes (net radiation, sensible heat, latent heat, and ground heat) remain zero for all instances. As the latent heat demand of 2.45 MJ for evaporation of 1 mm/d water (at 20°C) is known, the ET_c quantity can be derived by measuring or modeling the other components of this balance equation [Bow26] [AWH⁺11].
- Combination of an energy balance approach with an aerodynamic approach, like for example the Penman-Monteith-equation [Mon65] used for example in crop model AquaCrop. Here, ET_c is modeled by three meteorological variables: Effective radiation balance [W/m^2], air water sturation deficit [hPa], water vaporation saturation gradient (depending on air temperature) [hPa/K], and by two evaporation resistances: The aerodynamic restistance (depending on canopy height and structure, as well as on wind terms) [s/m], and the mean stomatal resistance (representing the water supply of the crop) [s/m].

Concluding, the determination of ET_c -data requires instrumentation and methods able to model the above described complex physical principles. To date, in a number of studies the a.m. different ET-modeling approaches are comparatively examined referring to the applicability of models to different crops [AWH⁺11], environmental conditions [STSH07] [XS01], timely and spatial resolutions [SC15] [GDNM⁺09], and measurement requirements [APHJ11] [FP13]. On the other hand, ET-based irrigation systems are tested in the field for practical use [DDM09] [KMD⁺16] [AR07]. Here, the input variables are a crop specific coefficient K_c , and measured/modeled weather data (i.e. air temperature, solar irradiation, wind speed, and air humidity) to model the actual, local ET_o . The resulting ET_c represents the actual crop water release quantity in [mm/d] to be refilled by irrigation (and precipitation).

Causality mapping: Modeling steps are depicted in figure 2.1 (causality mapping overview) referred to as atmosphere system output variables. The input variable of an atmosphere-based irrigation approach is the sensed atmosphere system output

variable (considered at a certain time t_o) represented by the output signals for weather data for e.g. air humidity [%], air temperature [$^{\circ}\text{C}$], solar irradiation [W/m^2], or wind speed [km/h]. Alternatively, a combination can be used to describe ET. The output variables of an ET model-based irrigation approach are the irrigation time [h], as well as the volumetric irrigation water quantity to be applied per area [mm/d]. Here, transpiration is assumed being an empirically determined share of total ET. This irrigation quantity equals the crop water release for a defined time period. The conversion of the considered input term into the output term is basically implemented by (i) the (empirically determined) correlation between actual local weather conditions and evapotranspiration quantities (ET_o), the (ii) (empirically determined) share of transpiration at total evapotranspiration (ET_c), and the (iii) (empirically determined) crop specific water release behavior (K_c).

2.4 Comparative Remarks

In practice, soil-based approaches are commonly used for irrigation scheduling [PKM09] [ACB15]. Most crop models are also including a soil water balance concept defining the quantity of water extractable by plants [BWB06]. Soil-based irrigation is appraised by [Jon04] as being not particularly accurate but substantially robust for different environmental conditions. Soil system-based methods allow an easy and practical application, also because water content measures directly indicate an irrigation volume to be applied. On the other hand, position and a large number of potential sensing locations reduce accuracy and generalization of measurements [Jon04]. Furthermore, all water balance modules are sensitive to the holding capacity of the soil, the depth explored by the roots and the climatic evapotranspiration [BWB06]. In addition, water balance approaches are assessed of being susceptible to cumulative errors [JS14] [Jon99]. Another drawback of soil-based methods is that physiological reactions of plants depend directly on plant tissue water status. The latter in turn is stated to depend not only on soil water status, but also on water flow characteristics through the plant varying according to the evaporation conditions for the plant [Jon04].

Plant system-based methods for water status monitoring are appraised to measure stress responses directly, integrate more effects than soil-based methods, and are potentially more sensitive [Jon04]. Drawback of those concepts is still a backlog in research and development [Jon04]. Plant-based methods are limited in use, as they can provide though an indication for the need and potentially also for the timing of irrigation, but not (yet) the determination of the irrigation water quantity needed [CBE⁺05] [BML14] [Jon99] [MAC⁺07].

Advantages in using an atmosphere-based water balance approach for irrigation purposes are seen e.g. in low sensing requirements and consideration of weather data [PKM09]. Though, evapotranspiration approaches are generally assessed not being implemented uniformly, as "*models have large variation in the prediction of ET, both in methodology and result*" [ASA15]. In [GFP⁺15] for example different approaches for ET modeling are compared and indicate that the results differ depending on season and particular weather condition. Further, in [ZB04] in total 84 experimental studies of crop water productivity values (actual yield divided by actual ET in [kg/m³]) for four irrigated crops were reviewed. A low correlation between crop yield and evapotranspiration was found (r^2 of 0,09-0,39). Besides the information loss due to simplification by modeling, errors deriving from measurement systems are seen to be the cause for limited information value in the experiments considered [ZB04]. Additionally, using transpiration values for determination of irrigation quantities does not consider e.g. compensation effects in different rooting depths like enhanced root development which might be feeded back to multi-layer water soil balances [LdJB01]. Further, equating transpiration with root water uptake does not consider plant internal processes, e.g. changes in plant hydraulic conductances [CBP⁺14]. Incidentally, an irrigation concept deducing a crop water demand only from plant water release neglects irrigation requirements caused by e.g. percolation or leaching of salts [APRS98].

Regarding deduction of irrigation variables, an overview about the described characteristics of the different approaches is shown in table 2.2. The detection, time, and quantification of irrigation necessities can either be derived from a plant system external water supply deficit, or from a plant system internal water supply status. Soil system-based irrigation is implemented either based on water balance considerations, or on empirical water content/potential trigger thresholds. Both approaches consider solely a plant external water supply deficit and do not include consideration of plant dynamic behavior. The determination of irrigation variables is soil system-based. Soil-based irrigation is targeted to optimize soil water availability. Plant system-based irrigation is implemented either based on plant water status considerations (water balance or water content/potential), or on water stress response trigger thresholds. All approaches consider plant dynamic behavior. The determination of the irrigation variable 'time' is plant system-based, but the determination of the irrigation variable 'quantity' is implemented soil- or atmosphere-based. Plant-based irrigation is targeted to maintain plant water status. Atmosphere system-based irrigation is implemented either based on energy balance considerations, or on thermodynamic approaches, or on a combination of both. In these models plant dynamic behavior is not included or only to a limited extend (by a correction factor). The determination of irrigation variables is atmosphere system-based. Atmosphere-based irrigation is targeted to refill water release (evapotranspiration).

Table 2.2: System-theoretical description of irrigation approaches [KS17] (Abbr.: Soil: Composition c , structure s , hydrol. process h , cultivation i , water content/precipitation swp ; Plant: Morphology m , water uptake u , water release r , characteristic pc ; Tissue: Distance d , resistance re , capacitance ca ; Potentials: Pressure pr , matrix ma , osmotic o , gravitational gr ; Air: temperature at , humidity ah , evaporation ev , condensation co ; Radiation ra ; Wind terms wt)

System	Soil	Plant	Atmosphere
Boundaries	Upper: Soil and root surface Lower: Not consistent	Plant surface	Upper: Not consistent Lower: Soil and plant surface
Components	Organic/anorganic matter, solid, liquid, gaseous phase	Root/shoot/leaf, sym-/apoplast, xylem, plant/ tissue/cell	Nitrogen, oxigen, argon, water vapor (1-3%)
State variables	$wss=[c,s,h,i]^T$	$wsp=[m,u,r,d,re,ca,pr,ma,o,gr]^T$	$wsa=[at,ev,co,ah,ra,wt,pc,swp]^T$
Processes	Water intake, release, movement	Water uptake, release, movement, physiological processes	Evaporation, condensation, water movement (wind)
Dynamics	Potential gradients, gravity, osmotic gradient	Water potential/osmotic gradient, gravity, dynamic behavior	Air vapor saturation, temperature, wind, irradiation, species
System output variables	Water content: Weight/volume, electrical conductivity/resistivity, or permittivity Water potential: Pressure, energy per volume/mass, or weight	Water status: Amount-, energy-, or content related Stress response emission: e.g. Leaf temperature	ET-quantity: Depth, volume, or energy Transpiration share of ET: Percent
Model target	Water availability	Water status or stress response	Water release
Model input variables	Water balance: Soil type, water content, water intake/release Water content or potential: Soil type, trigger threshold	Water balance: Species, soil water content, water uptake/release Water content or potential: Species, trigger threshold Stress response: Species, trigger threshold	Energy balance: Latent heat of vaporization, initial soil water content, evaporation energy data Aerodynamic methods: Weather data, empirical relation to ET Combined approaches
Irrigation variables	Time and quantity	Time	Time and quantity
Plant dynamics	No consideration	Plant water status and/or Stress response	No or limited consideration (K_c -adjustment)

Crop models consider all three systems including system transitions (soil-plant, plant-atmosphere). Plant dynamic behavior is considered in the module for plant water use by water limited yield reduction functions. Potentially, an atmosphere-based correction factor is included as well. The determination of the irrigation variable 'time' is potentially plant system-based, but the determination of the irrigation variable 'quantity' is only implemented soil- or atmosphere-based. Crop model-based irrigation is targeted to optimize water consumption related to yield.

It can be concluded, that to date plant dynamic behavior is directly considered only in plant-based irrigation approaches and to a limited extend in atmosphere-based ones. A respective consideration in soil-based approaches is not implemented. Further, the irrigation variable 'time' can be detected based on all approaches. On the other hand, the irrigation variable 'quantity' is only implemented based on soil or atmosphere variables. Deficit irrigation is targeted on a water supply aligned to the actual plant water status and specific dynamic plant behavior. Therefore, for this purpose the determination of both irrigation variables ('time' and 'quantity') should be primarily plant system-based. Resulting, none of the investigated irrigation approaches provides all variables necessary to irrigate based on the actual dynamic crop water demand for deficit irrigation purposes. This indicates fields for further research.

3 Water-based growth control

In this chapter the methodological approach for experimental modeling of dynamic plant behavior and water-based open-loop control of growth is described. First, a short introduction to growth-related plant adaptive behavior due to stress stimuli is given. Following, experimental data collection and processing is explained. Based on that, the derived state machine model is introduced. Then, the open-loop control approach is presented and illustrated as Trellis-diagram. For validation, statistical hypothesis testing is implemented. Finally, results and applicability of the proposed approach are summarized. Major parts of the following sections are published in [KS19b]. The applied method of model parametrization with NSGA-II optimization (section 3.2.3) is given in [BS17]. Numerical solution based on the described experimental data was implemented by Mrs. Jihin Rosmawati.

3.1 Plant adaptation: Missing link to growth control

During ontogeny plants adapt to environmental stress stimuli of a water deficit by different response and memory mechanisms [MSAT14] [MMFH⁺16] [LB17]. Responses to water deficits occur on different levels of organization (cell, tissue, organ, whole plant), aim either at improved water uptake or at reduced water releases, and include various processes like sustained root growth or stomatal closure [Hsi73] [Bra97] [Lös01] [SRH⁺09]. According to [Tre03] [TL13], memory mechanisms can be distinguished: First type of memory is termed ‘habituation’ [TS66], ‘priming’ [CBF⁺09], or ‘learning’ [The17] [GVB⁺16]. Information storage time is time-scaled in seconds to few days. The stored information is the characteristic of the stimulus. Memorization is expressed by an adjusted/modified stimulus transduction of a re-experienced stress stimulus. Second type of memory is termed ‘storage and recall’. Information storage time is time-scaled in days to months. Here, the stored information is not the stimulus itself, but the type of response to the stimulus (e.g. the metabolic reaction). Memorization is expressed by a rapid re-activation of an integrated response to a set of stimuli. This classification of memory processes is not always distinct, transitions between the forms are possible [Tre03] [TL13].

Adaptation processes include sensing (e.g. of increasing soil water potential), response (e.g. production of abscisic acid (ABA)), memory initialization (e.g. by priming or epigenetic modification), and recall of stored information [Tre03] [TL13] [Lic96] [LL16]. Adaptation can result in decreased dead time (time between sensing and response) [MMFH⁺16], decreased (harmful stimuli) or increased (harmless stimuli) perception threshold [TL13], reduced response intensity [DFA12], or increased metabolic activity [WVJ⁺14] when a stress stimulus is re-experienced within memory

storage time. Adapted plants show higher resilience to re-experienced environmental stress stimuli compared to not adapted plants, also increasingly if plants are exposed to repeated stress stimuli (training) [DFA12] [WVJ⁺14] [AAKHS14] [CBP⁺14].

Concluding, plants have the ability to ‘operate’ under suboptimal conditions and to re-equilibrate resources for growth, reproduction, and defense according to environmental conditions. Further, similar to the super-compensation model [Jak77] or the strain-stress-adaptation model [SHK11] in sport science plants adapt dynamically to repeated stress stimuli (training).

Major challenge for sustainable application of deficit irrigation methods is to control the plants related to their individually optimal water supply state(s). This control problem requires establishing a feedback structure including the plant system (model) (instead of e.g. soil-based water availability control). Generally, models describing yield formation subject to water inputs are available, e.g. AquaCrop (crop water productivity model, FAO [SRH⁺09]). Here, plants dynamical behavior due to water deficit is introduced by linear yield reduction functions reflecting the effects of water stress on yield [BWB06]. Restrictively, the application of these crop models for deficit irrigation optimization purposes are limited, because of the very small number of plant-based (instead of soil- or evapotranspiration-based) parameters describing the related dynamical behavior [KPKS12] [LIS⁺16]. Using an adequate model of dynamic plant behavior, the introduction of the plant system into the control loop would provide the opportunity to pursue different water-based optimization strategies, e.g. alignment of growth to predicted precipitation events. Included into a control loop (input: water; output: growth) the water supply state determination must relate directly to growth/yield factors, so that the commonly used water supply states ‘full irrigation’, ‘mild stress’, and ‘high stress’ can be determined by plant-based variables representing growth or yield formation, e.g. leaf elongation. Here, the distinction of the different states must be defined by relevant thresholds. To date, most stress-related thresholds for plant-based output variables described in literature refer to stress incipience, i.e. transition of ‘well-watered’ state to a state of first stress symptoms [WA02] [Jon04] [Jon07]. Plant-based thresholds for the transition of a ‘mild stress’ state to a ‘high stress’ state, or an evaluation whether the detected symptom still belongs to a ‘mild stress’ state or already to a ‘high stress’ state, could rarely be found. If plants are able to cope with certain suboptimal environmental conditions and to recover from deficit situations, the pure identification of a stress incipience is not sufficient to develop control approaches comprising adaptive behavior, as the behavior beyond stress incipience is not covered.

3.2 Deficit irrigation state machine model

3.2.1 Experimental set-up

The test rig consists of four growth stations placed in a rectangle and consisting of tables with superstructures for illumination, irrigation, measurements, and plant positioning. The test rig is located in a room (ground floor) of approximately 15 sqm, the windows are blacked and oriented north. Air temperature, air humidity, and ventilation are managed by university building equipment (pre-controlled ambient temperature and ventilation system). Illumination is automated with a clock timer (cf. figure 3.1).



Figure 3.1: Picture of experimental setup: Seramis pots. Plants are grown in pot filled with Seramis © clay granulate (1). Four growth stations placed in a rectangle and consisting of tables with superstructures (2) for illumination (a), irrigation (b), measurements (c), and plant positioning (d).

Seven irrigation experiments using maize plants (*zea mays*, Ronaldinio © (KWS)) in an early vegetative stadium EC11-EC15 were implemented. Deficit irrigation of maize is in scientific focus [CTD⁺19], [RIW⁺19] although maize being an annual and not particularly a cash crop like e.g. vegetables. Maize is generally adopted to dry environments with an evapotranspiration coefficient of about 200 l/kg dry matter, and water requirements of about 500 - 800 l/season, as opposed to e.g. wheat with an evapotranspiration coefficient up to 400 l/kg dry mass [Mai19]. However, in [DWJ16] the evaluation of data from peer-reviewed publications of the years 1980 to 2015 showed a higher sensitivity of maize to water deficits compared to wheat

with approximately double yield reduction as a result of a 40 % water reduction. Hence, the dimension of yield reductions due to water stress is different depending on species. Drought tolerant cultivars in turn are less affected by water deficits than drought sensitive ones. Here, peculiarities of different cultivars regarding stress avoidance (escape) and stress tolerance mechanisms have an effect [TLL⁺16]. Further, in [GJKA89] the onset of kernel number reduction due to water stress for maize was determined at 2 - 7 days after silking. Water stress ending prior to this critical stage had no influence on total yield, neither on kernel number, nor on kernel weight. Here, stress tolerance or compensation of stress effects by e.g. reduced ovule remission can be relevant for these effects. The most water stress sensitive period regarding yield was determined to be from day 2 up to day 22 after silking, in which kernel number and kernel weight (during grain filling period) were affected most by water stress [GJKA89]. Water stress after end of blister stage is again considered to be less critical for yield formation under water deficits. Hence, the dimension and the effect on kernel number and weight depend on stress timing. Recent deficit irrigation studies for maize investigate more in detail this stage-based water use behavior [CTD⁺19]. Furthermore, in some literature maize is described as anisohydric plant, having a loose control over leaf water potential, i.e. a slow stomatal response to soil water deficit compared e.g. to C3 plants [Tur74]. Contrary to that, in other studies maize is characterized as isohydric (sensitive stomatal response to soil water deficits) [Jon07]. In [FDF07] for instance this general behavioral distinction in isohydric and anisohydric is differentiated by additional patterns potentially contributing to elucidate this apparent contradiction.

Consequently, for the presented experiments it should be considered that test subject is one cultivar (Ronaldinio, KWS) of one species (maize) without specific consideration of appropriateness of this particular cultivar to drought. Further, investigations on dynamic plant growth behavior concentrate on early vegetative stage (up to EC15).

Experiments had a duration of 15 to 20 days each and were implemented under laboratory conditions for model parametrization and validation of the control approach. Environmental parameters were maintained fixed within certain ranges (cf. table 3.1) and apply equally to all plants within the same experiment. Despite certain variability of air humidity in the laboratory, the daily evapotranspiration rate (ETR) (plant plus substrate) remained very similar during the different experiments. Differences in ETR relate rather to size of individual plants than to environmental condition. Parallel measurement of evaporation rate of an equally prepared pot without plant showed nearly constant evaporation of +/- 2 g/d. At the beginning of the experiments the seeds were sown 4 cm deep into pots filled with 65 g Senamis © clay granulate (cf. figure 3.1). Maximum water holding capacity of a pot with 65g Seramis © clay granulate is about 60-65g water (no free water at the bottom of the pots). Therefore, substrate water content (WC) for full irrigation (stress

level ‘no stress’) is set at a substrate water content of 60 g (ml). The sample per experiment comprises 20 individual plants divided into four groups (A, B, C, D) of 5 plants each. In each experiment one or two groups of plants were fully irrigated (up to the maximum water holding capacity of the substrate of 60 g) and considered to serve as comparison groups. The other groups were exposed to different water deficit schedules. An overview about the performed irrigation strategies, denoted as stress level trajectories, for the seven experiments is presented in table 3.1. Air temperature and humidity were constantly measured by a standard digital hygro-/thermometer. The other measurements were implemented once to three times per day and aggregated to daily values where appropriate. Irrigation water was applied manually and precisely with an injection. Strict substrate water content was determined gravimetrically (Sauter © precision balance) by subtracting dry weight of the potted systems before first irrigation from total weight in the particular point in time.

The selected input variables are calculated as follows:

- Water content (WC) [g]: Gravimetric measurement of pot system including plant minus initial dry weight,
- Cumulative water content (CWC) [g]: Initially measured WC at experiment start plus total water applications up to the specific point in time,
- Evapotranspiration rate (ETR) [g/d]: Water content differential per day (24h) (without water application).

Leaf lengths of all leaves were measured manually with a curve ruler. Base point for ruler measurements was a sheet positioned on the top of the pots. The selected output variables are calculated as follows:

- Total leaf length (TLL) [cm]: Sum of lengths of all individual leaves of a plant,
- Total leaf elongation rate per Evapotranspiration rate ($\frac{TLEER}{ETR}$) [cm/g]: Quotient of TLER divided by ETR,
- Leaf appearance (LA) [d] or [g]: Time period [d] and CWC-differential [g] between leaf appearance of two successive leaves.

Table 3.1: Overview about experimental set-up and environmental conditions [KS19b]: Measured air temperature and humidity ranges, minimal/maximal daily evapotranspiration rate (ETR), test target, and groups' stress level sequences for each experiment denoted as: 0: no stress, 1: mild stress, 2: high stress. Sample per experiment: 20 plants in 4 groups (A, B, C, D) of 5 plants. Substrate material, fertigation, and illumination are equal for all experiments. (Abbr.: Evapotranspiration (ETR), developmental stages (EC13, EC15))

Parameter	Experiment number						
	1	2	3	4	5	6	7
Air temp. [°C]	21-24	21-23	21-22	21-25	18-22	20-22	20-22
Air humidity [%]	31-74	43-79	48-76	41-72	22-44	32-52	31-60
ETR EC13 (min)	4	4	6	6	5	5	4
ETR EC15 (max) [g/d]	18	19	15	20	20	18	24
Test target	Definition mild stress	Definition high stress	Stress distinction	Stress duration	Control test 1	Control test 2	Control test 3
Stress level sequence per group	A 0/0/0/0/0/1 B 0/1/2/0/0/0 C 0/0/0/0/0/1 D 0/1/2/0/0/0	A 0/0/0/0/0/1 B 0/1/2/0/1/2 C 0/1/2/2/0/0 D 0/1/2/2/2/2	A 0/0/0/0/0/1 B 0/1/0/1/0/1 C 0/1/0/1/0/1 D 0/1/2/2/0/0	A 0/1/0/1/0/1 B 0/0/0/1/0/1 C 0/1/0/0/1/0 D 0/0/0/1/0/0	A 0/0/0/0/0/0 B 0/0/0/0/0/0 C 0/1/0/1/0/1 D 0/1/0/1/0/1	A 0/0/0/0/0/0 B 0/1/0/1/0/1 C 0/1/0/1/0/1 D 0/0/0/0/0/0	A 0/1/0/1/0/1 B 0/0/0/0/0/0 C 0/0/0/0/0/0 D 0/1/0/1/0/1
Substrate	Seramis © clay granulate						
Fertigation	0.25 (Seramis © liquid fertilizer)						
Illumination	14h/d(Phillips TC-L, 2x 75 W,6500 K,30000 lx, appr. 300mol/m ² /s ⁻¹)						

3.2.2 Model description

Following conceptual understanding of the physiological relations due to soil/substrate desiccation is used to model adaptive plant behavior due to water stress (figure 3.2): Minor variations in water availability in the soil are considered to be unnoticed by plants as the signal value (e. g. soil water potential) remains below a certain sensing threshold of the particular plant (dotted line).

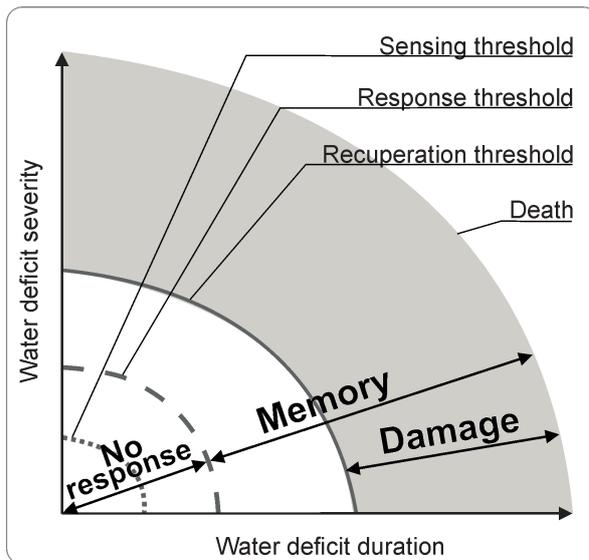


Figure 3.2: Concept of water stress levels based on water supply thresholds [KS19b]

No water stress: Below response threshold

Mild water stress: Between response and recuperation threshold

High water stress: Above recuperation threshold

A signal value exceeding this sensing threshold leads to the sensing of a reduced water availability by the plant. Here, the sensing threshold denotes the lowest signal value the plants can still detect by their senses (esthesia). In this model, sensing per se does not result in activation of adaptation/memory mechanisms. This activation is only started, if the sensed signal value exceeds a plant internal, critical threshold, the response threshold (dashed line), requiring adaptation in behavior to perpetuate operativeness. A sensed signal value below response threshold is considered to be uncritical for operativeness. Adaptation includes ‘reactions’ like stomatal closure (adaptation to immediate stimuli), as well as ‘memory’-initiation (adaptation to future stimuli). This adaptation to water deficits is possible (and growth limitations are reversible) as long as the recuperation threshold (solid line) for physiological processes is not reached. Here, recuperation denotes the ability of the plant to perpetuate operativeness despite reduced input quantities. Beyond this recuperation

threshold the plant experiences injuries, which are not reversible leading to a sustained limitation in growth and development. Relevant for the presented approach is the ability of plants to memorize stress events. Therefore, the term ‘memory’ is used to denote adaptive behavior in this model. The plant water supply state or a putative stress state are considered to be inner states of a plant emerging from a continuative desiccation. Based on a.m. conceptual understanding the process of desiccation can be distinguished into the states ‘no stress’ (below response threshold), ‘mild stress’ (between response and recuperation threshold), and ‘high stress’ (above recuperation threshold). In this study, the model concentrates on the experimental parametrization of the two thresholds (response and recuperation threshold) based on growth parameters. A plant system-based model describing plant growth subject to irrigation treatments is developed (figure 3.3) to serve as basis for the growth control approach.

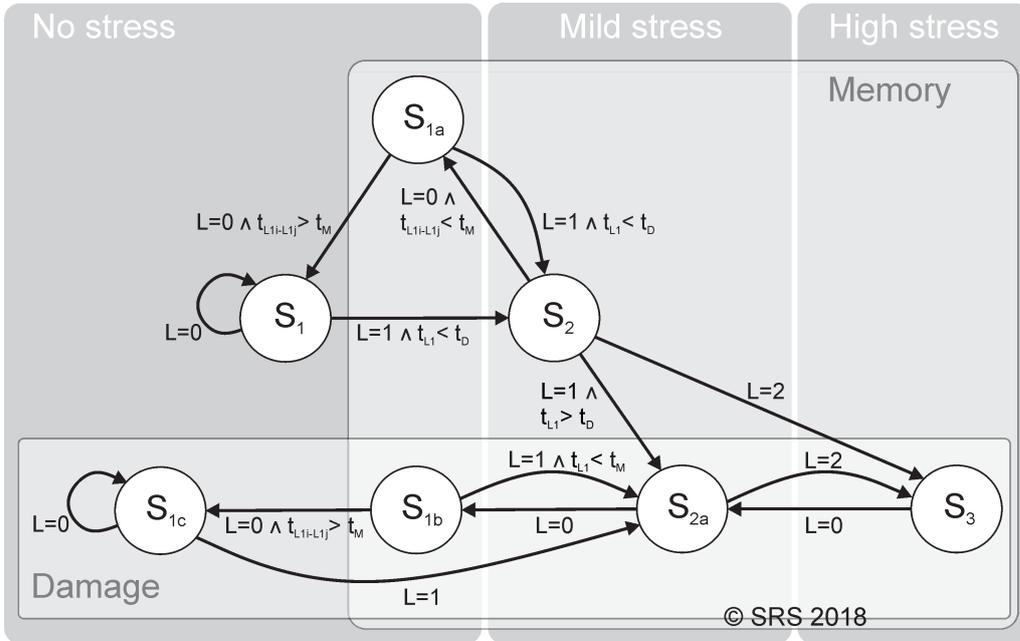


Figure 3.3: State machine model of plant behavior due to water stress [KS19b]: In compliance with defined transition conditions (arrows) the plant ‘switches’ from one state S_i to another state S_j (circles). Transition conditions are

- $L =$ Stress level with $L=0$ (no stress), $L=1$ (mild stress), $L=2$ (high stress),
- $t_M =$ Maximum memory time,
- $t_D =$ Maximum stress duration time,
- $t_{L1} =$ Time duration of stress level $L=1$ (L_1), and
- $t_{L_i-L_{1j}} =$ Time between the successive stress levels L_{1i} and L_{1j} .

Dynamic plant behavior is described as state machine model based on the discrete distinction of the plant water supply state variables ‘no stress’ (L_0 : stress level $L=0$), ‘mild stress’ (L_1 : stress level $L=1$), and ‘high stress’ (L_2 : stress level $L=2$). The latter are determined based on measured leaf elongation rate (LER) differentials due to different substrate water contents. In addition, the plants’ states are determined by two plant internal parameters:

‘Memory’: This parameter represents the plant’s capacity for remembering (memory) after experiencing mild stress. The parameter is activated in stress level L_1 ‘mild stress’ and deactivated in stress level L_0 ‘no stress’ if a re-activation (training) does not take place in due time (memory time t_M). This means, if the time period between successive stress levels L_1 (denoted as $[t_{L_{1i}-L_{1j}}]$) is longer than memory time t_M , the capacity for remembering is deactivated (reversible). The parameter denotes the adaptive behavior of growth recuperation after a mild stress (recovery) and can take the values ‘memory off’ (M_0 : memory level $M=0$) or ‘memory on’ (M_1 : memory level $M=1$). Memory is existent in states S_{1a} , S_{1b} , S_2 , S_{2a} , and S_3 (cf. figure 3.3).

‘Damage’: This parameter represents the existence of a plant’s dysfunction (damage) after experiencing ‘high stress’. The parameter is activated either in stress level L_2 ‘high stress’, or in stress level L_1 ‘mild stress’ lasting for more than a critical time duration. The latter means, if the time duration of an experienced mild stress (‘stress duration time’ $[t_{L1}]$) is longer than a maximum affordable stress duration period t_D a dysfunction is eventuated. Once activated, this parameter cannot be deactivated (not reversible). The parameter denotes the physiological injury caused by a stress beyond recuperation threshold resulting in a sustained growth reduction after re-irrigation (no recovery, possibly repair) and can take the values ‘damage off’ (D_0 : damage level $D=0$) or ‘damage on’ (D_1 : damage level $D=1$). Damage is existent in states S_{1b} , S_{1c} , S_{2a} , and S_3 (cf. figure 3.3).

Hence, the plant states S (circles) are described by the vector

$$S = [L, M, D]^T, \text{ with}$$

$$L = f(\text{water demand, water availability}),$$

$$M = f(L_1, t_{L_{1i}-L_{1j}}),$$

$$D = f(L_2, t_{L1}),$$

$$t_M = \text{Memory time,}$$

$$t_D = \text{Maximum stress duration time,}$$

$$t_{L1} = \text{Time duration of stress level } L_1 \text{ (} L=1 \text{), and}$$

$$t_{L_{1i}-L_{1j}} = \text{Time between the successive stress levels } L_{1i} \text{ and } L_{1j}.$$

Starting point for the state machine model is state S_1 representing a plant which did not experience any water stress before. State S_1 is denoted as (0/0/0) for (‘no

stress’/’memory off’/’damage off’). Withdrawal of water resulting in an exceedance of the response threshold (stress level L_1 : $L=1$) leads initially to a transition from state S_1 to the memory-initiating state S_2 denoted as (1/1/0) for (‘mild stress’/’memory on’/’damage off’). Henceforward, the state transitions depend on irrigation schedule: Re-irrigation (return to stress level L_0 : $L=0$) initiates the transition to state S_{1a} (0/1/0). Alternatively, further water withdrawal resulting in an exceedance of the recuperation threshold (advance to stress level L_2 : $L=2$) initiates the transition to the damage-initiating state S_3 (2/1/1); or constant mild stress (continuation in stress level L_1 : $L=1$) results in transition to the damage-initiating state S_{2a} (1/1/1). Further transitions along the depicted model states operate correspondingly. End point for the state machine model is not defined, as model target is an intended deficit irrigation till harvest.

Model characteristics and assumed growth behavior of the states are:

- S_1 : vector (0/0/0); reference growth behavior (comparison values),
- S_2 : vector (1/1/0); reversibly reduced growth,
- S_3 : vector (2/1/1); irreversibly reduced growth,
- S_{1a} : vector (0/1/0); increased growth,
- S_{1b} : vector (0/1/1); irreversibly reduced growth,
- S_{1c} : vector (0/0/1); irreversibly reduced growth,
- S_{2a} : vector (1/1/1); irreversibly reduced growth.

Here, the states S_1 , S_2 , and S_{1a} are the desirable states for deficit irrigation purposes, as growth is not irreversibly affected due to immoderate water stress.

Transitions between states are illustrated by arrows and denote the conditioned change from one state to another if defined conditions are fulfilled. Besides the task-specific definition of states also the definition of transition conditions is part of the modeling. Here, the transition conditions are defined using

- the actual stress level,
- the stress level experienced in the previous instance,
- the time between successive stresses, and
- the actual stress time duration

as variables used in suitably designed conditions.

3.2.3 Data-driven model parametrization

Modeling and data driven-based identification of related parameters is realized using a state machine approach assuming unknown but constant state descriptions and unknown but constant transition conditions. The unknown parameters are defined by applying NSGA-II optimization used for a training and test procedure. Introduction and details are given in [BS17].

Assuming a known/given topology about the qualitatively distinguishable behavior of plant growth (figure 3.3) related mathematical equations can be applied to describe the state dependent leaf elongation L for the assumed different states depending on the lifetime increment ΔLT . Here the structural behavior is assumed as similar, the details are assumed as different (different parameter setting). Related state-dependent parameters as well as the parameters of the given transitions conditions are calculated via optimization using NSGA-II standard software.

Model parametrization is implemented based on the equations for

$$\text{State } S_1: \quad \Delta LT = a_{10} + \frac{a_{11}}{1+e^{a_{12}(L-a_{13})}} + a_{14}L + a_{15}L^{a_{16}} + \frac{a_{17}}{1+e^{a_{18}L}},$$

$$\text{State } S_{1a}: \quad \Delta LT = a_{20} + \frac{a_{21}}{1+e^{a_{22}(L-a_{23})}} + \frac{a_{24}}{1+e^{a_{25}(L-a_{26})}} + a_{27}e^{a_{28}(1-L)},$$

$$\text{State } S_{1b}: \quad \Delta LT = a_{30} + \frac{a_{31}}{1+e^{a_{32}(L-a_{33})}} + \frac{a_{34}}{1+e^{a_{35}(L-a_{36})}} + a_{37}e^{a_{38}(1-L)},$$

$$\text{State } S_{1c}: \quad \Delta LT = a_{40} + \frac{a_{41}}{1+e^{a_{42}(L-a_{43})}} + \frac{a_{44}}{1+e^{a_{45}(L-a_{46})}} + a_{47}e^{a_{48}(1-L)},$$

$$\text{State } S_2: \quad \Delta LT = a_{50} + \frac{a_{51}}{1+e^{a_{52}(L-a_{53})}} + \frac{a_{54}}{1+e^{a_{55}(L-a_{56})}} + a_{57}e^{a_{58}(1-L)},$$

$$\text{State } S_{2a}: \quad \Delta LT = a_{60} + \frac{a_{61}}{1+e^{a_{62}(L-a_{63})}} + \frac{a_{64}}{1+e^{a_{65}(L-a_{66})}} + a_{67}e^{a_{68}(1-L)},$$

$$\text{State } S_3: \quad \Delta LT = a_{70} + \frac{a_{71}}{1+e^{a_{72}(L-a_{73})}} + \frac{a_{74}}{1+e^{a_{75}(L-a_{76})}} + \frac{a_{77}}{1+e^{a_{78}L}},$$

with ΔLT denoting lifetime increment, and L denoting leaf elongation.

Based on the measured growth data and the described state machine approach the model parameters are calculated as follows:

- **Response threshold** (transition of stress level L_0 to L_1)
42.9 - 45.19 g substrate moisture: plants are in stress level L_0 as long as water availability is higher than 45.19 g (70 - 75 % substrate water holding capacity).
- **Recuperation threshold** (transition of stress level L_1 to L_2)
19.2 - 28.1 g substrate moisture: plants are in stress level L_1 as long as water availability is below 42.9 g but higher than 28.1 g. Further, plants are in stress level L_2 as soon as water availability drops below 19.2 g.
- **Memory time t_M** (maximum memory storage time)
2.77 days period between successive stress level L_1 stress events: plants lose memory of experienced stress levels L_1 (training) if a subsequent stress level L_1 occurs later than 2.77 days after the previous, experienced stress level L_1 .
- **Maximum stress duration time t_D**
(maximum duration of stress level L_1 till dysfunction)
2.74 days period duration of a stress level L_1 : plants also exceed the recuperation threshold, if the time duration of stress level L_1 exceeds the period of 2.74 days.

3.3 Open-loop control approach

The novel results examined here are based on the consequent use of the different stress levels, sequenced so that the plant growth can be controlled with respect to given targets. This approach is based on the assumption, that growth behavior of plants is significantly different in the different states. Based on this assumption following control targets can be formulated:

Plant height/biomass: If a mild stress L_1 tends to reduce plant height and biomass production, a targeted irrigation can be used to control these variables e.g. substitutional for stalk-reducing substances.

Water consumption: If training of plants with periods of mild stress L_1 can be used to minimize plant water consumption in specific periods without substantial yield reductions, a targeted irrigation can be used to control plant water demands, e.g. targeted to precipitation events.

Harvest time: If a mild stress L_1 accelerates by trend physiological development (e.g. leaf appearance), a targeted irrigation can be used to control the timing of physiological stages and harvest time.

An overview about resulting (open-loop) control options based on potential alternative state trajectories are depicted in the Trellis-diagram (figure 3.4). Potential states S_i (circles) and state transitions (arrows) are shown in the sequence of instances (k).

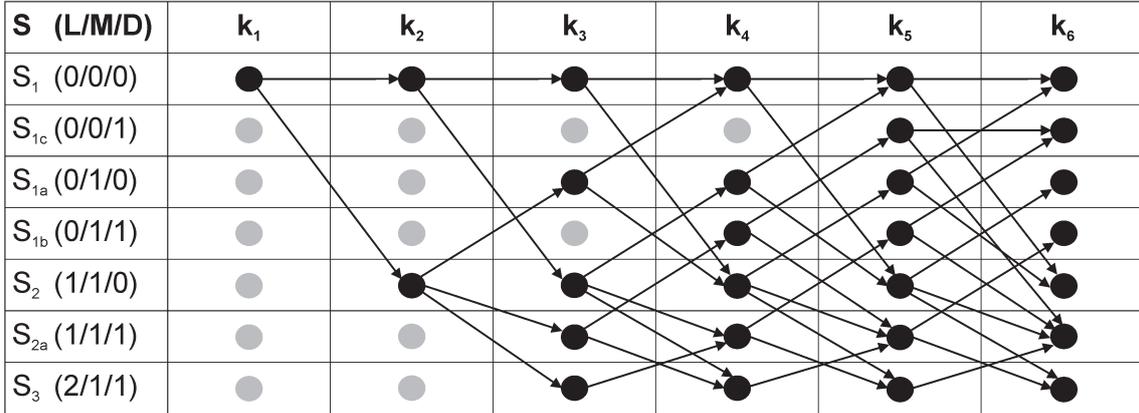


Figure 3.4: Trellis-diagram of stress state trajectories for open-loop growth control [KS19b]: Arrows denote state transitions, black circles denote realizable states, grey circles denote not realizable states in instance k_i .

S_i : State

k_i : Instance

L: Stress level

M: Memory level

D: Damage level

Similar to approaches in sport science, these state trajectories (training sequences) can be differentiated according to targets (e.g. endurance, susceptibility) by varying input trajectories (e.g. number of repetitions, number of series) and thresholds (e.g. stress severity, duration). Restrictively, these options are only valid within physiological constraints of the species and individual plant: Every athlete is limited by its physiological capabilities set by the genome [Bou12]. Further, trainability is limited by the natural processing speed and the limits of the characteristic features [SGB17]. Therefore, growth follows a natural plan of developmental stages and is bound to restrictions in time and direction.

3.4 Proof of concept control approach

3.4.1 Experimental validation

For model validation experimental data are analyzed for selected variables based on data sets for different water stress states.

Variables: Following water input and growth output variables are investigated:

- Water content (WC) [g]: Instantaneous availability of substrate water content,
- Cumulative water content (CWC) [g]: Total substrate water availability relating to a period in time or in ‘growth’,
- Evapotranspiration rate (ETR) [g/p]: Daily water consumption (plant plus substrate),
- Total leaf length (TLL) [cm]: Total growth/plant height at point in time or ‘water’,
- Total leaf elongation rate per evapotranspiration rate ($\frac{TLE}{ETR}$) [cm/g]: Daily growth performance in terms of water consumption,
- Leaf appearance (LA) [d] or [g]: Speed of physiological development in terms of time or CWC.

Water stress states: As described, the relevant water stress state S_i depends on:

- Stress level L (no stress, mild stress, or high stress), representing the instantaneous substrate water content,
- Memory level M (with or without memory) representing a plants’ adaptive response,
- Damage level D (with or without damage) representing a plants’ dysfunction,
- Sequence of stress levels,
- Period of stress duration, and
- Period between consecutive stresses.

Measurement data are grouped according to stress states S_1 , S_2 , S_3 , S_{1a} , and S_{2a} . The model states S_{2b} , S_{1b} , and S_{1c} are not included in the following analysis, as these states are considered not to be desirable for deficit irrigation purposes because of reduced productivity due to high stress events. The analysis of states is based on the comparison of the states before or at a first stress (S_1 , S_2 , S_3) with the relevant state after the stress concerned: State S_1 is compared to state S_{1a} , state S_2 is compared to state S_{2i} , and state S_3 is compared to state S_{2a} (cf. figure 3.5).

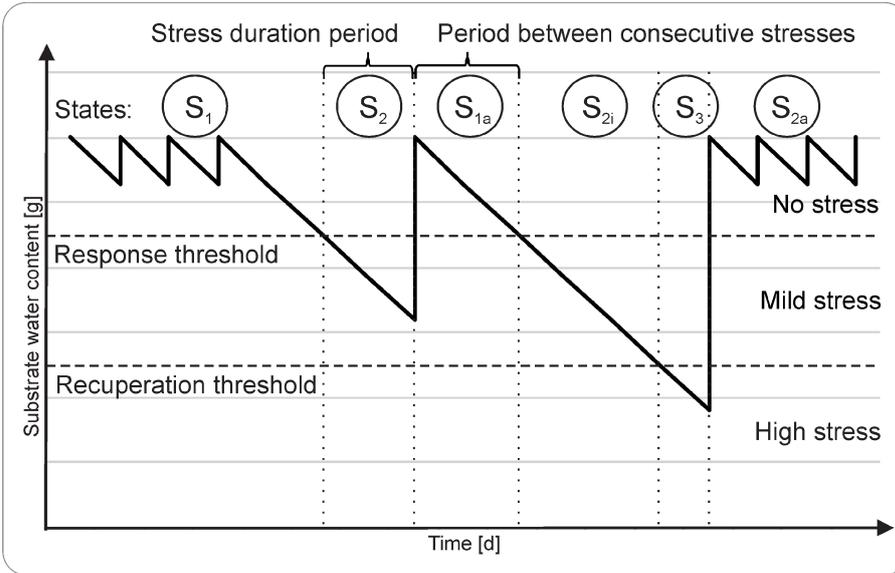


Figure 3.5: Illustration of data selection for state determination based on substrate water content [KS19b]: Daily evapotranspiration results in substrate water content reduction (decreasing values) refilled by irrigation (abrupt value increase). Definition of states S_i depends on current substrate water content (above/below response or recuperation threshold), and on sequence/duration of stress levels (trajectories).

Samples: Total sample consists of 135 individual plants from 7 experiments. Measurement time series are discretized according to the a.m. schematic procedure and then grouped according to the affiliation to different states. The samples for state-based comparison of growth behaviors are structured as follows

- S_1 : No stress prior to first stress; 135 individuals with 975 measurement points,
- S_{1a} : No stress after mild stress; 55 individuals with 470 measurement points,
- S_2 : First mild stress; 90 individuals with 220 measurement points,
- S_{2i} : Successive mild stresses; 55 individuals with 125 measurement points,

- S_3 : High stress: 35 individuals with 275 measurement points, and
- S_{2a} : No stress after high stress; 30 individuals with 180 measurement points.

Total plant growth: In figure 3.6 total plant growth (TLL) related to cumulative substrate water content (CWC) for each stress state is shown. Increasing stress (S_1 to S_2 to S_3) results in decreasing growth rates. Experience of a first mild stress in S_2 results after re-irrigation in S_{1a} in recovery of growth rate. At re-experienced mild stresses within memory time in S_{2i} growth rate is not reduced, but instead, slightly increased compared to the initial mild stress in S_2 as well as compared to full irrigated state S_1 . The latter behavior is defined as memory in the model. After the experience of a high stress in S_3 a re-irrigation does not result in a recovery of growth rate in S_{2a} . This is defined as damage in the model.

Growth performance: In figure 3.7 total leaf elongation rate (TLER) related to evapotranspiration rate (ETR) for each stress state is shown. Increasing stress (S_1 to S_2 to S_3) results initially in substantially decreased growth performance in S_2 . As stress proceeds (S_2 to S_3), growth performance increases again in S_3 and even outperforms the fully irrigated state S_1 . This is attributed to the activated memory (adaptation), which is initiated in state S_2 . Experience of a first mild stress in S_2 results after re-irrigation in S_{1a} in a recovery of growth performance which is highest of all states. At re-experienced mild stresses within memory time in S_{2i} growth performance is also increased compared to the initial mild stress in S_2 as well as compared to full irrigated state S_1 . The latter is as well attributed to the defined memory. After the experience of a high stress in S_3 a re-irrigation does not result in an increased growth performance in S_{2a} , as performance is already high in S_3 .

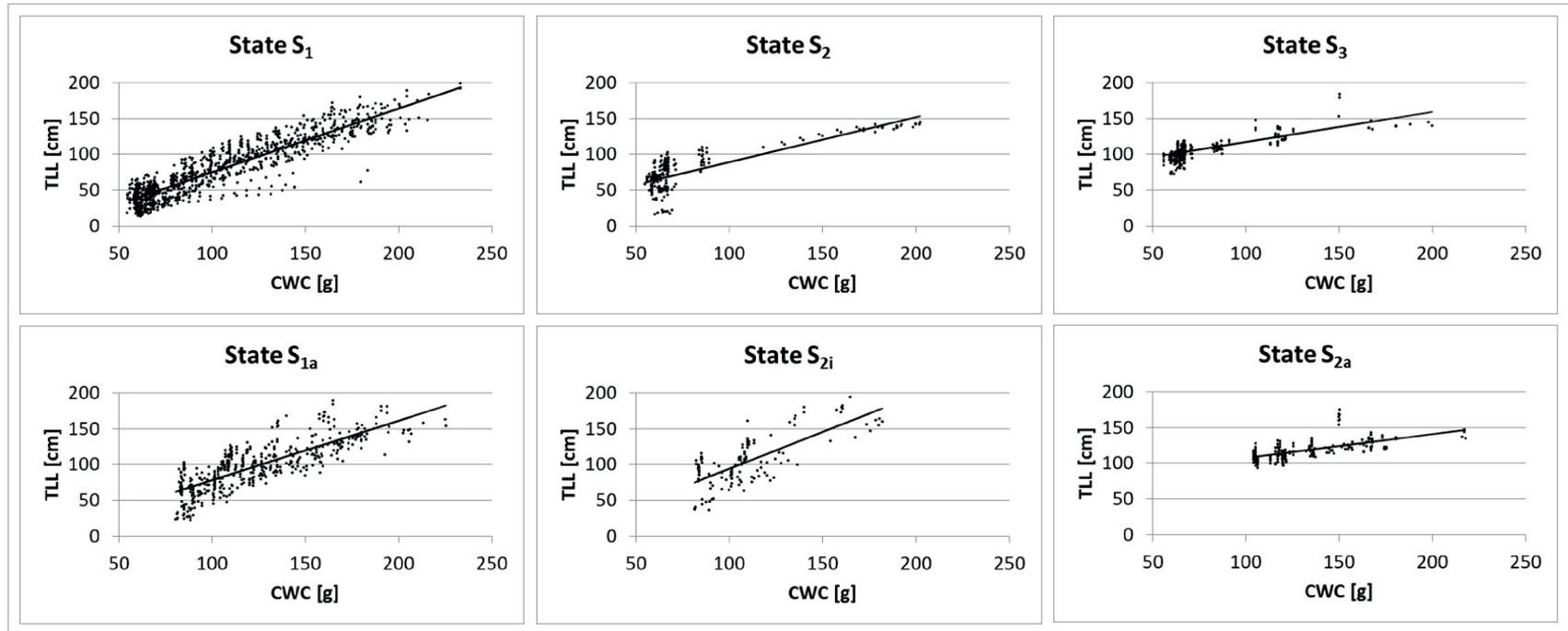


Figure 3.6: Water stress state-based analysis of growth behavior [KS19b]: State-based comparison of total plant growth (total leaf length: TLL) related to cumulative water content (CWC) in states S_1 (no stress/memory off/damage off), S_2 (first S_2) (mild stress/memory on/damage off), S_3 (high stress/memory on/damage on), S_{1a} (no stress/memory on/damage off), S_{2i} (successive S_2) (mild stress/memory on/damage off), and S_{2a} (mild stress/memory on/damage on).

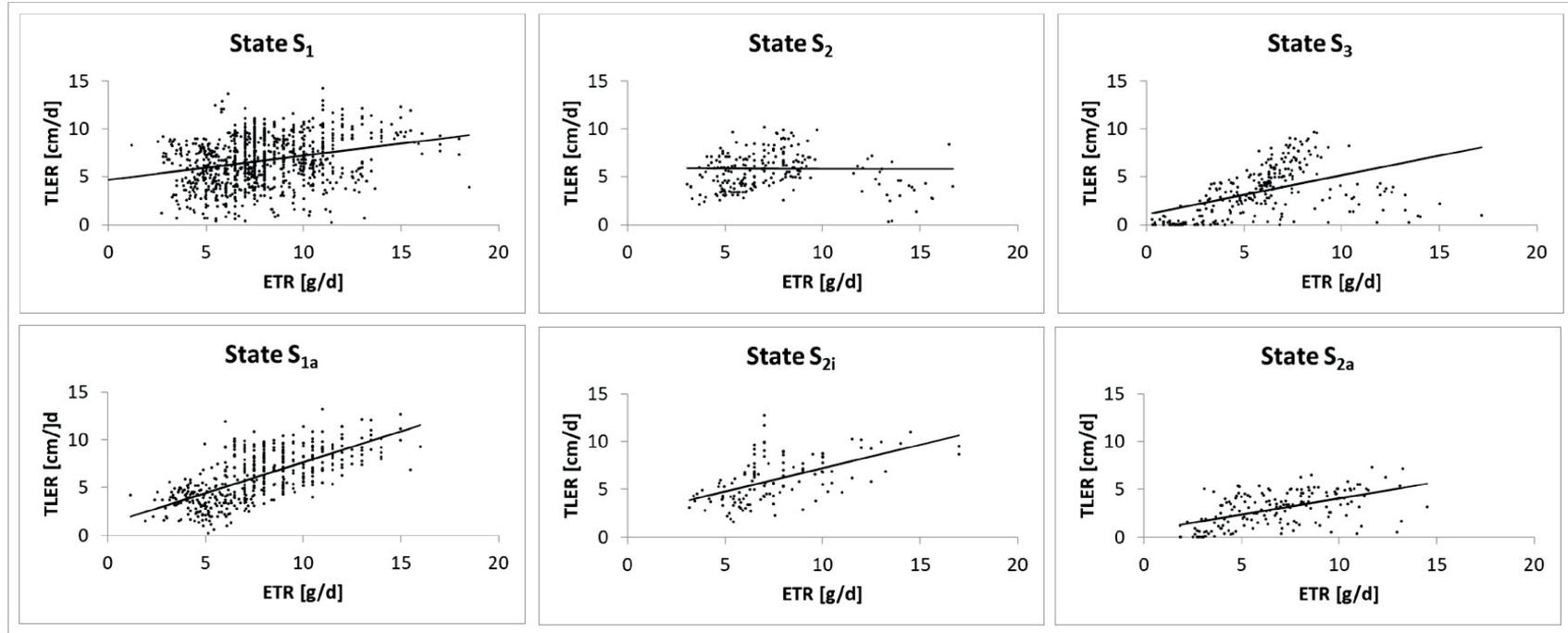


Figure 3.7: Water stress state-based analysis of growth performance behavior [KS19b]: State-based comparison of total leaf elongation rate (TLER) related to evapotranspiration rate (ETR) in states S_1 (no stress/memory off/damage off), S_2 (first S_2) (mild stress/memory on/damage off), S_3 (high stress/memory on/damage on), S_{1a} (no stress/memory on/damage off), S_{2i} (successive S_2) (mild stress/memory on/damage off), and S_{2a} (mild stress/memory on/damage on).

Leaf appearance: In table 3.2 the effect of a water stress event on the period in time [days] or cumulative water content [g] between the appearance of successive leaves is shown. Here, stress event is denoted as an experienced stress level L_1 or L_2 in the time period up to the appearance of the respective leaves.

Table 3.2: Effect of water stress events on leaf appearance [KS19b]: Values are given as period in time [d] or cumulative water content [g] between the appearance instance of successive leaves (between leaf 3 and leaf 4 (EC13-14) as well as between leaf 4 and leaf 5 (EC14-15)). No data are included for EC14-15 for stress level L_2 , as only two 5th leaves did appear due to high stress.

Stage	Time CWC	Stress level 0			Stress level 1			Stress level 2		
		Min	Med	Max	Min	Med	Max	Min	Med	Max
EC13-14	[d]	3	4	12	2	4	8	4	6	10
	[g]	125	154	195	112	142	172	55	60	66
EC14-15	[d]	6	7.5	13	6	7	13	-	-	-
	[g]	187	220	>260	167	210	>260	-	-	-

In this experiment, the experience of mild stress events accelerates by trend the appearance of successive leaves in terms of time (median: minus 0.5 days (7 %) for leaf 5 compared to non-stressed plants) and in terms of cumulative water content (minus 10 g (5 %) for leaf 5 compared to non-stressed plants). The experience of a high stress delays significantly the appearance of successive leaves in terms of time (median: plus 2 days (50 %) for leaf 4 compared to non-stressed plants; leaf 5 only appeared at two of all highly stressed plants within experiment duration).

3.4.2 Hypothesis testing

Statistical validation is implemented using different hypothesis testing methods to reflect the different testing targets (e.g. variance homogeneity, correlation) and data characteristics (e.g. distribution, paired/unpaired) [Ben12] [How16]:

- Test for Gaussian distribution is performed for all groups for growth variable TLL on a daily basis. The used tests are Shapiro-Wilk- [SW65] and Anderson-Darling-test [AD52]. Gaussian distribution was expected, but could not be proved for all days by both tests. Therefore, parallel testing with hypothesis tests requiring Gaussian distribution and distribution-free tests is implemented.

- Test for correlation is performed for all variable combinations for all groups and states. The used tests are Bravais-Pearson-test (Gaussian) [Gal89] and Spearman-test (distribution-free) [Spe10].
- Test for linear regression [Gal94] is performed for all variable combinations for all groups and states.
- Test for mean differences is performed for the state combinations S_1-S_{1a} , S_2-S_{2i} , and S_3-S_{2a} for the variable combinations TLL-CWC, TLER-ETR, and TLER/ETR-CWC. The used tests are T-test (Gaussian, paired and unpaired) [Stu08], Mann-Whitney-U-test (distribution-free, unpaired) [MW47], and Wilcoxon-test (distribution-free, paired) [Wil45].
- Test for variance homogeneity is performed for the state combinations S_1-S_{1a} , S_2-S_{2i} , and S_3-S_{2a} for the variable combinations TLL-CWC, TLER-ETR, and TLER/ETR-CWC. The used tests are F-test (Gaussian, unpaired) [Fis60], Leneve-test (Gaussian, unpaired) [Lev60], and Conover-test (distribution-free, unpaired) [CJJ81].

Measurement data for the states are unpaired for data from different plants, but paired for data of the same plant (before and after a stress event). Therefore, this data set is mixed (partially paired data) related to dependency. According to [GY17] these data sets should be analyzed with tests for paired data. Parallel testing with tests for unpaired data support the findings to a large extend. Inconsistent results comparing the results of the different tests only refer to mean and variance differences between state S_2 and S_3 , and to variance difference between state S_1 and S_2 .

Confidence level for all tests is set to 95%. Test power is set to 80% to calculate minimum sample size n [Coh88]. Effect size is measured using cohen's d (mean differences), cohen's f^2 (regression) [Coh88], and variance quotient ($\text{var1}/\text{var2}$) (variance homogeneity). In tables 3.3 - 3.6 the relevant results of statistical validation are summarized.

To conclude the directed relation between input variable water and output variable growth for water-based growth control a correlation and regression analysis is implemented. Here, this refers to the parameter combination growth (TLL) with cumulative water content (CWC) (table 3.3) as well as to total leaf elongation rate (TLER) with evapotranspiration rate (ETR) (table 3.4).

Table 3.3: Relation of growth (TLL) to cumulative water content (CWC) [KS19b]*

States	S_1	S_2	S_3	S_{1a}	S_{2i}	S_{2a}
r	0.89	0.63	0.82	0.64	0.60	0.65
R^2	0.83	0.65	0.60	0.64	0.55	0.36
Cohen's f^2	4.88	1.85	1.50	1.77	1.22	0.56
n	5	12	8	6	11	11

Table 3.4: Relation of growth rate (TLER) to evapotranspiration rate (ETR) [KS19b]*

States	S_1	S_2	S_3	S_{1a}	S_{2i}	S_{2a}
r	0.27	0.17	0.62	0.70	0.59	0.55
R^2	0.06	0.00	0.19	0.46	0.29	0.28
Cohen's f^2	0.06	0.00	0.23	0.85	0.40	0.38
n	81	<u>215</u>	12	9	14	16

* Correlation coefficient r : Very weak <0.2 , middle $0.4-0.6$, very high >0.8 ,
Coefficient of determination R^2 : Weak 0.1 , middle 0.25 , high >0.4 ,
Effect size Cohen's f^2 (R^2): Weak $0.02-0.14$, middle $0.15-0.34$, high >0.35 ,
Minimum sample size n : Required sample size at 80% test power [Coh88] (Underlined numbers of n denote non-representative sample size in this experiment).

These two variable combinations show values of high and very high correlation. Total leaf elongation rate (TLER) shows very weak correlation to water consumption (ETR) for not yet/fully memory initialized states S_1 and S_2 . This behavior changes abruptly to a high to very high correlation in all states after experiencing the first mild stress. Accordingly, for the same states the correlation between growth (TLL) and cumulative water content (CWC) is decreased. This is interpreted as a switch from a 'hydrological time'-based growth towards a 'usage-bound' growth at the moment of memory initialization.

Proof for the potential implementation of different stress state trajectories (and accordingly growth performance trajectories) is realized by hypothesis testing for mean differences and variance homogeneity between the relevant states for the performance parameter TLER per ETR in [cm/g] (cf. tables 3.5 and 3.6). The continuous substrate desiccation resulting in a transition from state S_1 to S_2 to S_3 leads to a continuous reduction in growth performance variance, which is not detectable between the directly successive states S_1 to S_2 and S_2 to S_3 with 95% confidence level. This difference is detectable comparing directly state S_1 with S_3 . At the same state comparisons, mean is changing significantly. This change is minimal between S_1 and S_2 . The observed behavior can be interpreted as growth performance reduction due to increasing water stress. Further, in state S_2 the usage-bound growth is initiated, leading to a reduction in non-growth related water consumption also in state S_3 .

Table 3.5: Test for mean difference between states (TLER/ETR) [KS19b]*

State pair	S_1-S_2	S_2-S_3	S_1-S_3	S_1-S_{1a}	S_2-S_{2i}	S_3-S_{2a}
Mean \neq	yes	yes	yes	yes	no (0.07)	yes
Cohen's d	0.06	0.93	0.65	0.18	0.14	0.37
n	750	9	17	<u>197</u>	<u>249</u>	49

Table 3.6: Test for variance homogeneity between states (TLER/ETR) [KS19b]*

State pair	S_1-S_2	S_2-S_3	S_1-S_3	S_1-S_{1a}	S_2-S_{2i}	S_3-S_{2a}
Variance \neq	no (0.33)	no (0.12)	yes	yes	yes	yes
Var1/Var2	2.28	1.09	2.51	3.54	2.01	2.15
n	44	<u>2888</u>	39	39	62	53

* Test for mean differences: Wilcoxon-Test [Wil45] (only connected data of this sample),

Test for variance homogeneity: Conover-Test [CJJ81],

Effect size cohen's d (mean differences): weak <0.5 , middle $0.5-0.8$, high >0.8 ,

Effect size Var1/Var2: variance quotient,

Minimum sample size n: required sample size at 80% test power [Coh88] (Underlined numbers of n denote non-representative sample size in this experiment).

Differences in mean and variance between state S_1 and S_{1a} (comparison of full irrigated state without and with memory) are significant confirming the assumed effect of growth performance increase after re-irrigation. Differences in mean and variance between state S_2 and S_{2i} (comparison of mildly stressed states at memory initiation and with existing memory) are only significant for the variance, means are more similar. This finding supports the assumption that memory is initialized in the first mild stress leading already to a certain increase in growth performance despite decreasing growth (TLL). Full increase in mean growth performance is then reached after a certain time. Differences in mean and variance between state S_3 and S_{2a} (comparison of highly stressed state with re-irrigated states after high stress) are again significant, although in a negative sense: The mean after re-irrigation is even smaller than in high stress, and variance is additionally reduced.

Summarizing, plant growth behavior is significantly different for the defined states and variables. Further, sample sizes are generally representative for the relevant connections (with few reservations). Here, very low relation of growth rate and evapotranspiration rate in state S_2 (cf. table 3.3) requires a larger sample to prove a relation. Further, small effect size referring e.g. to the difference in median for leaf appearance (cf. table 3.2) or to the mean difference between states S_2 and S_{2i} (cf. table 3.4) also requires a larger sample to prove a significant effect of mild water stress on these variables. However, according to the presented results it can be concluded, that discretization and sequencing of stress states for growth control purposes is productive.

Growth control: In table 3.7 the comparison of relevant growth results due to different irrigation schedules is shown. Here, overall performance of all plants experiencing a mild stress (MS) are compared to all plants never experiencing any water stress (FI). Further, memorized fully irrigated state (S_{1a} within t_M) (‘usage-bound’ growth) is compared to non-memorized fully irrigated state (S_1 after t_M) (‘hydrological time’-based growth).

Table 3.7: Comparison of mean growth results [KS19b]: Comparison between full irrigated plants (FI: 45 plants) and plants experiencing at least one mild stress during the experiment (MS: 55 plants). Additionally, for 25 plants of group MS the values for state S_{1a} within t_M (full irrigated and memorized state) and state S_1 after t_M (full irrigated and de-memorized state) are shown.

	TLL [cm]	TLER [cm/d]	CWC [g]	ETR [g/d]	TLER/ETR [cm/g]
FI (reference)	143,94	6,48	224,00	8,12	0,82
MS (% of FI)	136,23 (94 %)	6,23 (96 %)	189,17 (84 %)	7,32 (90 %)	0,91 (110 %)
S1a (within t_M) (% of FI)	-	9,68 (149 %)	-	10,19 (125 %)	1,21 (147 %)
S1 (after t_M) (% of FI)	-	6,75 (104 %)	-	8,96 (110 %)	0,75 (91 %)

Mean total leaf length (TLL) and mean total leaf elongation rate (TLER) of plants experiencing at least one mild stress during the experiment are slightly reduced compared to the mean TLL (- 6 %) and TLER (- 4 %) of plants never experiencing any stress event. At the same time, mean cumulative water content (CWC) and mean evapotranspiration rate necessary to accomplish the growth of the mildly stressed plants are reduced as well (CWC: - 16 %; ETR: - 10 %). This results in an increased mean growth performance (TLER/ETR: + 10 %) of mildly stressed plants. Moreover, the comparison of growth performance variables (TLER, ETR, TLER/ETR) of mildly stressed plants during memory time (t_M) (state S_{1a} in the period of 2 days after second or third mild stress) with the same plants after the end of memory time (state S_1 in the period beyond 4th day after a second or third mild stress) shows a reduction in growth performance: During memory time mean growth performance (TLER/ETR) is increased by 47 % compared to the mean of fully irrigated plants. This increase disappears after the fourth day without re-initiation of memory. This result is interpreted as reversibility of the proposed memory factor and as evidence for the return from a ‘usage-bound’ growth performance to a ‘hydrological time’-based.

Concluding, for deficit irrigation purposes (without damage initiation), the proposed trajectories represent an intended alteration of two growth performance ranges: ‘hy-

drological time' or 'usage-bound'. Periods of 'hydrological time' performance range (de-memorized full irrigation state S_1) are used for maximum total growth, by trend reduced growth speed, and minimum water use efficiency. Periods of 'usage-bound' performance range (memorized states S_2, S_{1a}, S_{2i}) are used for similar or intendedly reduced total growth, by trend accelerated growth speed, and maximum water use efficiency.

3.5 Summary and discussion

Based on experimental data, a state machine model of plant dynamic behavior was developed. Here, plant growth behavior is described in terms of stress level, memory level, and damage level, denoting inner states of the plant and resulting from varying water inputs. Control (open-loop) of plant growth is implemented by the introduction of stress trajectories (sequences), resulting in an intended, event-discrete transition between desired stress states. Control targets are growth (biomass), growth speed, and water use. Results of statistical validation (hypothesis testing) confirm the validity of the approach.

The presented approach is a first proof for the potential introduction of dynamic, adaptive plant behavior into irrigation control approaches. Superior target is the purposive alignment of plant growth to water availability (and not vice versa) as well as to yield targets based on an open-loop irrigation control. Innovations are the active utilization of training mechanisms (adaptation) in the water-growth-causality chain, and - opposite to commonly used irrigation approaches - the control (optimization) of the plant growth (control variable) instead of the water availability (soil water content) or consumption (evapotranspiration).

The utilization of training mechanisms permits the exploitation of the plants' natural capabilities to reduce inputs (e.g. water, chemicals) and undesirable impacts (e.g. water dissipation, environmental load). This aims at an improved input efficiency and sustainability. Moreover, training could potentially also be applicable for other inputs (e.g. chemicals). Plant 'vaccination' [Lun16] can also be seen as a related approach. Further, the 'trainability' of plants can be considered as breeding target. The introduction of plant growth control into the irrigation task permits an improved synchronization of plant water demand with soil water availability and - even more interesting - the tuning of physiological developments only based on water inputs (time and quantity).

Despite the potential of the proposed approach, some factors require more scientific efforts before implementation in the field is possible.

Sensitivity of plants versus precision of measurements: The presented response and recuperation thresholds are both determined to be reached at an early stage of soil water depletion. Under the presented experimental conditions, the initiation of an adaptive response occurs when water availability is just shortly (24h) about 15-20 g lower than total substrate water holding capacity. This represents a response threshold at a water availability of about 70 - 75 % of total substrate water holding capacity. The recuperation threshold is reached at a water availability between 40 - 30 % of total substrate water holding capacity. The initiation of adaptive behavior for training purposes without producing damages requires therefore the precise control of water deficits between these two thresholds. This requires an adequate water stress detection method and sampling rate, which is precise enough to detect deficits already at an early stage of soil water depletion. Moreover, the exact plants' response and recuperation thresholds are stochastic variables. This requires precise methods to detect the water deficit state plant individually.

Field capacity versus recuperation threshold: The commonly known water availability thresholds (field capacity, permanent wilting point) differ from the determined response and recuperation thresholds:

- Field capacity denotes the drained soil state after total soil water saturation. Practical guides mention 80 % to 100% of field capacity to be optimal for plant growth, and 50 % of field capacity as a benchmark for stress incipience [APRS98] [Min15].
- Permanent wilting point denotes the soil water content at which plants are not any more able to extract water from the soil. As a result, plants wilt and die.

The mentioned soil-based benchmark of 80 % field capacity for optimal growth is defined similarly to the determined plant-based response threshold in the proposed approach, although at a lower water content value (response threshold: 70 - 75 % of substrate water holding capacity).

The introduced recuperation threshold (at about 40 % substrate water holding capacity) is not represented by the common water availability concept, implicating that water stress is generally not positive. Scientific studies are required to specify the recuperation level of further crops and vegetative states in order to make use of targeted deficit irrigation strategies without loss of earnings.

Growth control versus remote sensing: Measurement of plant growth variables for stress state detection is productive for growth control purposes, as the output variable is directly linked to yield. Restrictively, the remote sensing of plant growth parameters in the field is still limited, mainly because of actual limitations of image-based methods for detection of e.g. object overlapping, light reflectance, or 3D growth. A number of remote sensing approaches for the detection of water stress in plants are investigated [MBB⁺18] [KFS17] [SDMMH⁺17], but those measure other variables than growth (for example plant water content (by e.g. reflectance), or consumption (by e.g. leaf temperature)). Here, the clear relation between output variable (e.g. leaf temperature) and growth/yield still has to be evaluated in order to confirm and to specify the observability of growth/yield by the selected measurement signal.

Summarizing, the introduction of water deficit training procedures into cultivation methods can be one option to reduce the water dissipation in irrigated agriculture. Moreover, the inclusion of plant dynamic behavior into the irrigation control loop permits to pursue growth targets based on water input trajectories. More scientific work is necessary for precise stress detection and remote state observation. Here, the inclusion of additional stress thresholds like the a.m. recuperation threshold are helpful to utilize the productive fraction of plants' stress adaptation.

4 Remote sensing approach

In this chapter, the potential to observe water stress-related plant behavior based on leaf temperature oscillation is investigated. First, known stomatal oscillation behaviors and relation to water deficits are introduced. Second, specification for experimental leaf temperature measurement is given. Third, used frequency analysis methods are briefly introduced. Fourth, frequency analysis results are presented. Finally, applicability of leaf temperature oscillation analysis for remote sensing of water stress is discussed. Major parts of following sections are published in [KS19a].

4.1 Leaf temperature oscillations

Leaf temperature measurements are utilized to monitor transpiration and the water status of crops [JIRPJ81] [LGT⁺06] [WYW⁺10] [MS12]. Leaf temperature depends on the energy fluxes between leaf and surrounding atmosphere and hence on numerous climate variables (e.g. air temperature and humidity, radiation, wind speed) and on plant physiological variables (e.g. stomatal aperture) [Gat68] [JKRO16]. Water availability below maximum plant water demand (water deficit) impacts leaf temperature by the consecutive reduction of transpiration due to stomatal closure [Hsi73] [DSCU10]. Transpiration results in reduced leaf temperatures due to evaporative cooling, particularly if environmental conditions tend to rise considerably leaf temperature, e.g. high air temperatures [Gat68] [Mon81]. Hence, reduced transpiration leads to an increase in leaf temperature. Perpetuation of transpiration in spite of a water deficit is a key process to regulate leaf temperature under water stress and maintain operativeness of tissues [MU88] [UM88] [SOZ13].

The concept of leaf temperature measurement for water status determination is related to the water flow processes through and within the plant [JIRPJ81]. Here, the model of water balance related to these flow processes is based on the thermodynamic water potential relations between soil, plant, and atmosphere as well as between the different compartments within the plant [JT98]. Water potential is a thermodynamic variable used to express water availability of a system or to model water movements between systems [Tho96]. Here, the driving force for water movements are water potential differences between single compartments. Water and water vapor ‘flows’ from areas of high water potential to areas of low water potential. A change in water potential in one area (e.g. an increase of air water potential due to high air temperatures or low air humidity) results in changes in water potentials in the adjacent areas, either by changing flow rates (e.g. increased transpiration rate), or by active water potential adjustments by the plant (e.g. increased osmotic pressures in roots to increase water uptake), or by physiological changes in the plant due to sustained water stress (e.g.

wilting) [JT98]. The detailed interaction between the variables determining plant water balance are complex and still subject of scientific studies [BJ73] [PFJ03a] [TSP15].

Relevant section of these processes for the presented study is the causality between transpiration rate and leaf temperature to indicate potential water stress. Transpiration rate depends on stomatal conductance, and under constant evaporative conditions stomatal conductance depends on stomatal apertures [Lös01] [TSP15]. Consequently, stomatal apertures determine the quantity of plant water transpiration (*ceteris paribus*) and hence the degree of evaporative cooling of the leaf surface [Gat68] [APRS98] [MVCMT15]. According to Webb [Web98] stomatal apertures are influenced by

- environmental (e.g. air CO₂-concentration),
- physiological (e.g. xylem abscisic acid (ABA)-concentration), and
- circadian (e.g. light-dark-cycles)

signals. Here, these input signals are further distinguished into plant system external and internal signals. Major external signals are light, CO₂-concentration, air temperature and humidity, wind speed, and the degree of a water deficit. Major internal signals are the concentration of phytohormones, particularly ABA, and endogenous circadian signals [Web98] [HW15]. Signals triggering the opening of stomata are [DGH78] [GML07] [AFNN11]

- low CO₂ concentrations,
- high air humidity,
- wind, and
- high light intensities;

whereas signals triggering the closure of stomata are

- high CO₂ concentrations,
- water deficit,
- ABA, and
- darkness.

Further, oscillation of stomatal aperture is described in several studies [Bar71] [URC88] [Web98] [Sha06] [WdCRM10] [Joh15]. Different oscillation frequencies are attributed to following major factors.

- Circadian rhythms:

Oscillations with periods of 23 - 26 h [Web98] are observed, where stomata of well-watered C3- and C4-plants are open in the days (light) and closed at night (darkness) [Bar71] [HW15]. Hence, oscillation frequency attributed to circadian rhythms is approximately 1/24 h.

The anticipation of the light-dark-cycles (stomatal opening before dawn and closure before dusk) was monitored [Web98] [HW15], hypothesizing that light is only one factor in this mechanism. Plant internal circadian rhythms are assessed to be a regulation mechanism for these anticipations as well as for physiological responses to external disturbances, e. g. water deficit [Web98] [CBP⁺14].

- Water deficit:

Oscillations are reported with periods of 15 min - 1 h for corn [Ape67] [Bar71], 12 - 18 min for Banana [ZRS⁺10], 20 min - 1 h for tomato [WdCRM10], and 30 min - 1 h for cotton [MSFB06]. These stomatal oscillations were in all cases observed indirectly by measuring either CO₂-uptake [Ape67], leaf turgor pressure and leaf transpiration [ZRS⁺10], water loss in weight [WdCRM10], or stomatal conductance [MSFB06]. Further, oscillating water hydraulic conductance in plants was measured [CBP⁺14]. Assembling the observations, the entire water-bearing system in plants is oscillating autonomously under water deficit (i.e. water transpiration and transport, turgor/volume, ion concentration, membrane potentials etc.) [Joh15]. This behavior is interpreted as synchronized hydraulic signal and at the same time a mechanism to prevent the xylem from cavitation [Ras70] [Bar71] [Sha06] [WdCRM10]. The latter conclusion is supported by the fact that pumps with oscillating pressurization can provide high pressures also at small flow rates, accompanied by reduced tip pressures [ESSW09] [MYH17]. Summarizing, oscillation frequency attributed to water deficits vary between 1/h (period of 60 minutes) and 5/h (period of 12 minutes). Water-related oscillations affect the entire water-bearing system.

In some studies, start/stop-conditions for water-related oscillations are stated: In [Ape67] oscillations in corn started “*only at a certain water deficit in the leaves*” and stopped at air humidity of 100 %. In [ZRS⁺10] oscillation in Banana started when leaf turgor was below 100 kPa. The latter could not be ascertained for all water-stressed banana plants in this study, despite reduced stomatal conductance. In [GDZTF14] leaf temperature measurements of water-stressed

and well-watered citrus trees are depicted. Here, leaf temperature oscillations are detected in both treatments, water-stressed and well-watered trees, starting in the morning and stopping in the afternoon. Summarizing, water-related stomatal oscillations are detectable, if plants are exposed to a water deficit. Further, also well-watered plants can develop stomatal oscillations.

- CO₂-concentration:

Oscillations due to variations of CO₂-concentration in the air are reported with periods of 2.5 - 5 min for corn [Ras65] [Ape67] [Bar71], and periods of 5 - 10 min in experiments with *Arabidopsis* [BGJ15]. CO₂-related oscillations are associated with Ca²⁺ oscillations in guard cells: if air CO₂ concentration is high, Ca²⁺ oscillation is low (period of 10 min) inducing stomatal closing; if air CO₂ concentration is low, Ca²⁺ oscillation is higher (period of 5 min) inducing stomatal opening [AFNN11] [HSV11] [BGJ15].

Beyond that, for other physiological processes oscillating behavior is described, e.g. for ion channel conductance [Sha06], or plasma membrane electrical properties [YZZ05]. These are assumed to have influence on stomatal apertures as well [YZZ05].

Concluding, the causality between stomatal aperture, transpiration, and leaf temperature implicates the determination of the water supply status of a plant by the measured leaf temperatures (=observability). Hence, this causality can be used as a model to describe system behavior with the input variables “water quantity” and “irrigation time”, the controlled system “plant”, and the output variable “leaf temperature”. As described above, leaf temperatures are oscillating as a result of oscillating stomatal apertures (*ceteris paribus*). Further, leaf temperature oscillations show different frequencies resulting from diverse internal and external input signals on the stomatal system, i.e. water deficit. The initial point of this work is the assumption that the water supply states of plants (fully irrigated, mildly, or highly stressed) can be described by state variables based on leaf temperature patterns including oscillation characteristics.

4.2 Leaf temperature measurements

Leaf temperature measurements were taken continuously during all experiments. For following investigation, leaf temperature data of an experiment of may 2016 are used. Here, substrate and irrigation application are implemented differently compared to a.m. description (cf. section 3.2.1):

Experimental setup also comprised 20 individual plants grouped in four groups (A, B, C, D) of five plants each. Plants were grown for nine days in Seramis © substrate. At vegetation stage EC11 - 13 the seedlings were transferred to individual mounting plates of acrylic glass fixing the plants' root system on germination paper (Hahnemuehlen 3644, 720 g/sqm) (cf. figure 4.1). Mounting plates were reversibly fixed in four hangers arranged in front of the Infrared (IR) camera (640x480 px, < 0.05 °C thermal sensitivity).



Figure 4.1: Picture of experimental setup: Germination paper. Maize seedlings grown on individual mounting plates of acrylic glass fixing the plants' root system on germination paper (1). Mounting plates are reversibly fixed in four hangers arranged in front of the Infrared (IR) camera (clocked orientation to each group of seedlings by PLC-controlled step motor) (2).

Infrared (IR) pictures (sampling period: 20 minutes) and germination paper moisture signals (sampling period: 2 hours) were taken automatically controlled by a programmable logic controller. Leaf temperature values were calculated as follows: Original IR camera signals (dimensionless) per pixel and time stamp were extracted from the camera. Measuring points (one pixel in the middle of the second leaf) were selected for all pictures manually from each IR picture. The temperature calculation is based on the original IR camera equations. This procedure allows for a subsequent

calculation of leaf temperature time behavior considering automatically dynamic variables (e.g. air humidity, air temperature). The results of the first experiment presented below are based on fixed variables for emissivity (0.97), air temperature (22 °C), and air humidity (24 %). Germination paper moisture was measured using the electrical conductivity of water. At two out of five mounting plates of each group resistance measurements were taken and compared to gravimetric measurements of applied irrigation amounts. Measurements of leaf elongation (sampling period: 24 h) were taken manually with a ruler.

Different irrigation regimes were applied to the four groups: In pretests it was determined that the total water holding capacity of each germination paper sheet amounts to 75 - 85 g water. Evapotranspiration per day was gravimetrically measured and accounts for approximately 20 - 25 g/24 h at the beginning of the experiment, increasing to up to 28 - 33 g/24 h as plants grow. First days after sowing all plants were fully irrigated until vegetation stage EC11 - 13 was reached. This point of time is denoted as starting time of the experiment (Day 0). Irrigation regime was adjusted for each group: First control group (A) was fully irrigated for the complete period (germination paper bottom in contact with water). Second control group (D) was not irrigated for the complete period. First test group (B) received no water till day 2.5. At this time first wilting symptoms were visible (hanging leaf tips, reduced turgor). Here, this state was denoted as mild stress. Irrigation for group B comprised 65 g water per plant (complete refill of total water holding capacity of the germination paper) and was applied manually at day 2.5. Second test group (C) received no water till day 3.5. At this time serious wilting symptoms were visible (leaves are bend down) and nearly no water (< 10 g) was stored in the germination paper. Here, this state was denoted as high stress. Irrigation comprised 80 g water per plant (complete refill of total water holding capacity of the germination paper) as well applied manually at day 3.5. This experimental procedure results in following basic sets of stress levels:

- Full irrigation (FI): The amount of available water in the germination paper is 50 g - 85 g. This applies to all plants at the first 1.5 days of the experiment (20 plants) as well as to group A (5 plants) for the total duration of the experiment. Basic set of plants in stress level FI: 20 / 5.
- Mild stress (MS): The amount of available water in the germination paper is 20 g - 50 g. This applies to groups B, C, and D (15 plants) between day 1.5 and 2.5 of the experiment. Basic set of plants in stress level MS: 15.
- High stress (HS): The amount of available water in the germination paper is 0 g - 20 g. This applies to groups C and D (10 plants) between day 2.5 and 3.5 of the experiment as well as to group D (5 plants) between day 3.5 and the end of the experiment. Basic set of plants in stress level HS: 10 / 5.

The presented leaf temperature time behavior is characterized by abrupt temperature changes (grey, vertical lines) when illumination is switched on/off (day-night-cycle). Temperature signal gaps at these moments amount to 2.5 - 3 °C of the calculated temperature due to the sudden discontinuation of radiation. It is assumed that the determined difference in leaf temperature is not reflecting a real cool down of leaf temperature, but is mainly due to the radiation-based measurement technique of bolometric IR-cameras. To depict real cool down processes a data processing subtracting this known “virtual” temperature gap could be applied. The presented results are based on the original, unprocessed data, as only temperature differences between the irrigation treatments are considered, not absolute values. Restrictively, when evaluating leaf temperature behavior under the described, not sinusoidal illumination regime, transient transpiration behaviors due to the sudden light activation/discontinuation can possibly cause transient leaf temperature behavior until leaf temperature commute in similar level as in a natural environment (including dusk and dawn). One explanation for this behavior may be a delayed response time of the stomatal apparatus to external light signals (dead time) as described in [VCMM⁺17].

In figure 4.2 leaf temperature time behavior of exemplary one plant of each group (A1, B1, C1, D1) are depicted. Besides the mentioned day/night oscillation fixed to an artificial period of 24 h, different oscillations are detected regarding the temperature time behavior in figure 4.2: Oscillations of small amplitudes (<1 °C) and short periods (<1 d) in the days and partially also at nights (e.g. in solid lined circles), oscillations of higher amplitudes (1-2 °C) and longer periods (3 - 4 d) in the days (between dashed lines), and oscillations with amplitudes of approximately 1 °C and periods up to 5 days at nights (between dotted lines). Here, the time series is considered to be “raw” data. The different frequencies are superimposed with overlapping oscillations of different period durations and amplitudes. From this it can be stated that a visual, sinusoidal periodicity is not expected to be identified at this stage of analysis.

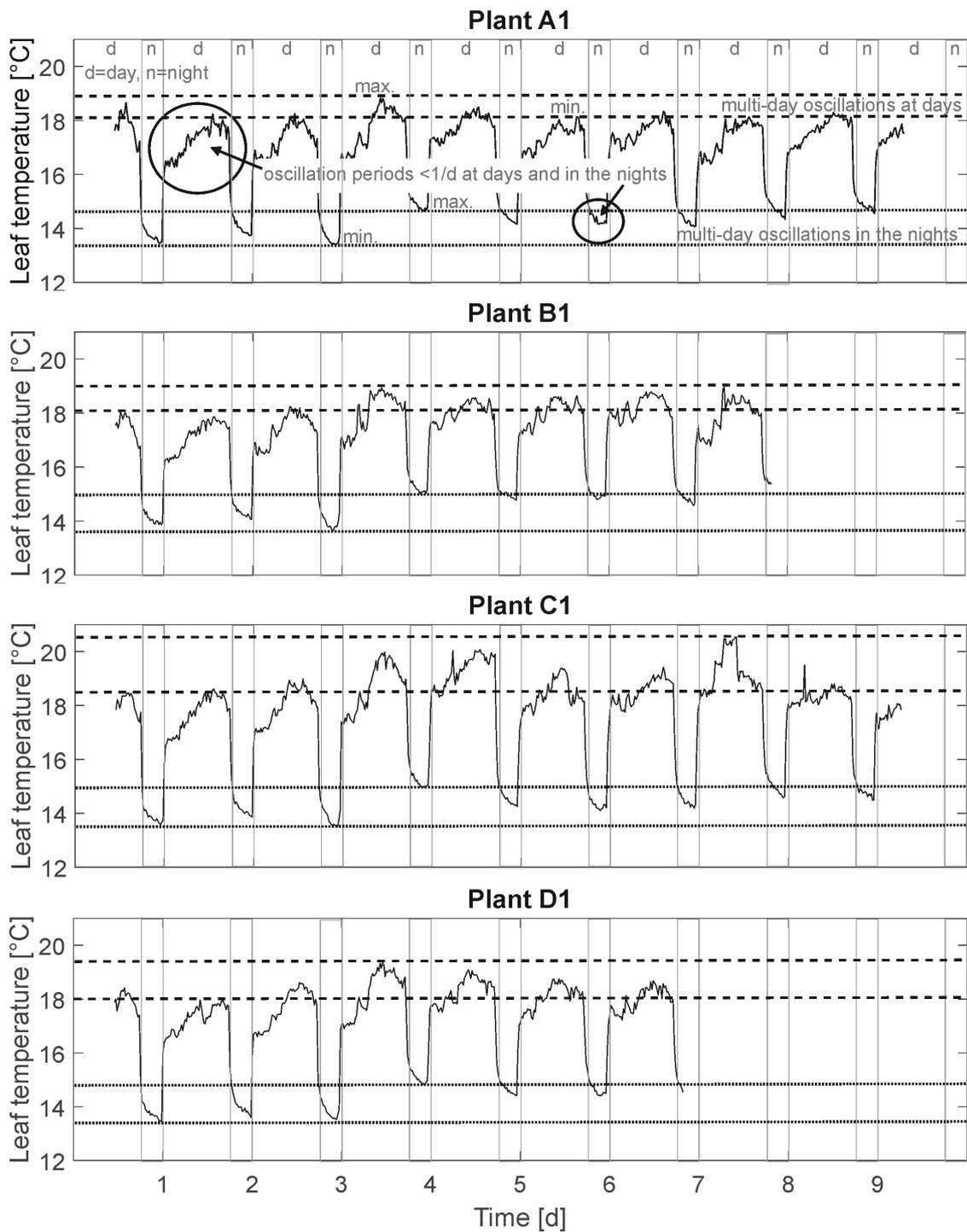


Figure 4.2: Leaf temperature time series of plants A1, B1, C1, and D1 [KS19a]
 Vertical lines: Illumination switch-on/-off (artificial day(d)-night(n)-cycle)
 Horizontal lines and circles: Superimposed oscillations
 - Days (dashed lines): Amplitude 1 - 2°C, period 3 - 4 days
 - Nights (dotted lines): Amplitude 1°C, period 5 days
 - Days/nights (circles): Amplitude < 1°C, period < 1d

4.3 Frequency analysis methods

Frequency analysis methods can be used to detect, distinguish, and quantify superimposed or hidden oscillations. By the standardized application of these methods to measurement data the specific behaviors, regularities, and sudden changes in frequencies and amplitudes can be analyzed. Further, signal noise e.g. due to disturbances of measurement devices can be identified more easily.

Restrictively, according to the Shannon-Nyquist-Theorem, the reconstruction of a signal based on equally spaced samples is possible, if the sampling rate equals or exceeds the double of the upper cutoff-frequency. This means, that frequency properties can only be reliably detected for frequencies fulfilling this theorem. In this study the sampling period for IR pictures was 20 minutes (sampling rate: $72/24$ h or $1/1200$ Hz). Thus, the upper cutoff-frequency is certainly less than $36/24$ h ($1/600$ Hz) representing a sampling period of 40 minutes. Therefore, only the measured frequencies below approximately $36/24$ h are considered in the following observations.

Following graphic accounts and explorative frequency analysis methods were applied to the presented leaf temperature time behavior of the plants:

Local Minima and Maxima (MM): Here, the inflection points, calculated by comparison with respectively neighboring raw temperature values, are simply depicted in a diagram to examine by visual comparison of line densities and lengths the differences in oscillation intensities/rhythms (cf. figure 4.3). This provides a first qualitative indication of irregularities and differences between the time series which could be investigated further.

Phase Portrait (PP): This method is not a FA method in a closer sense. The PP depicts graphically dynamic system behavior by trajectories (path of changes) of a state variable (here: leaf temperature) in the phase space (here: totality of all measured leaf temperature values). The considered signal value (leaf temperature) is plotted in a coordinate system against its first derivative (leaf temperature change rate, here with $\Delta t = 20$ minutes representing the sampling period) (cf. figure 4.4). The comparison of PPs (e.g. of a stressed plant with one of a non-stressed plant) can be used to visualize differences in dynamic system behavior related to equilibrium points (“similar” values occurring often) and vector field (all occurring values). This provides a first visual insight into dynamic properties like periodic time behavior or frequently occurring values.

Cepstrum (CEP): Cepstrum analysis is based on a double Fourier Transform and is used to detect common sources within a mix of resonances and related sidebands within a signal. The Fourier Transform is a mathematical method to decompose a signal (time series) into its different frequencies e.g. the different frequencies of an acoustic signal. Cepstrum represents a specific mathematical application of the Fourier Transform in order to detect ‘echoes’ of a specific source characterized by a whole-numbered multiple of a basic frequency. The method is used e.g. for vibration monitoring of machines with rotating machine parts. The reliable interpretation of a Cepstrum chart is only possible, if the value of the ‘peaks’ representing a sideband are obvious (e.g. the 3-fold of all other peaks). A higher similarity in peaks’ values and distributions cannot be rated. By applying Cepstrum analysis repeating periodic components in a signal can be detected, even at very small amplitudes (as long as the amplitudes are equal). The resulting Cepstrum of a time series represents the time period of one period length/duration of this periodic component of the signal (cf. figure 4.5).

Short Term Fourier Transform (STFT): The STFT is also based on the Fourier Transform, modified by the introduction of time windows with corresponding frequency spectrums. Frequency changes in time (e.g. due to stimuli or disturbances) cannot be detected by a ‘simple’ Fourier Transform, as this method is only applicable to stationary signals (without changing frequency properties). By applying STFT to a signal the temporal variation in the frequency spectrum of a signal can be represented (cf. figure 4.6). Restrictively, STFT does not appear to be in all cases the best method for FA, e.g. if short-term high-frequency signal components concur with slow variant low-frequency signal components as for example in Electroencephalography (EEG) signals (cf. [KK12]; Küpfmüller’s uncertainty principle, stating that a high time resolution, e.g. to detect the exact time of appearance of a certain frequency component, is not compatible with a high frequency resolution for exact frequency determination). Therefore, as the particular frequency components of the presented leaf temperature signal is unknown, the below described alternative methods are also applied to the signal.

Wavelet Transform (WT): The WT was developed to solve the named problem of an adequate frequency resolution for low-frequency signal components and an adequate time resolution for high frequency components of a signal. With WT the signal is separated into frequency adopted time sequences to analyze simultaneously the frequencies of different lengths in accordingly selected time windows [Far92] (cf. figure 4.7). As drawback of WT compared to STFT the lack of an amplitude representation in the analysis should be noted. The application of WT to a signal facilitates the frequency pattern recognition in signals, as signal components of different frequencies can be considered at the same time, although at different resolutions.

Stockwell Transform (ST): The ST is a recently developed and consistently enhanced FA method. The ST is based on a modified Short Term Fourier Transform (STFT) method adjusting the time-frequency-resolution automatically to the relevant frequency and hence combining the strengths of STFT and the Wavelet Transform (WT) i.e. a high time resolution and a high frequency resolution (cf. [Sto07]) (cf. figure 4.8). However, also this method is not always the optimal FA method for all applications, drawbacks are e.g. still the comparably high computational time needed to analyze big data volumes.

Hilbert-Huang-Transform (HHT): This time-frequency data analysis method includes an empirical mode decomposition part and a Hilbert spectral analysis part. First, an iterative algorithm is fragmenting the signal into so called Intrinsic Mode Functions (IMFs) representing the individual, superimposed oscillations. Second, a Hilbert spectrum analysis is applied to the IMFs to detect the instantaneous frequencies in time (cf. figure 4.9). The result represents a “*physically meaningful time-frequency-energy description of a time series*” [HW08]. Contrary to Fourier transform-based methods the HHT is an empirical approach utilizing the structure/characteristics of measurement data to detect oscillations of different kinds within the same signal. The method is supposed to uncover concealed physical relations and to facilitate the search for disturbance-initiated natural oscillations.

All a.m. methods (except MM and PP) are tools for signal processing procedures e.g. in control engineering, geophysics, speech recognition, or medical applications. As mentioned, each method has pros and cons. The selection of a certain method for a specific application should be based on considerations concerning the expected period durations and frequencies, the required resolutions, computational aspects, and the target of the study. In this study, caution is required if time series of different time duration are compared, e.g. with ST, as the duration/length of the time series has influence on the graphical representation of frequencies. For example, in figure 4.8, plant A: The diurnal sequence of amplitudes between 0.4, 0.2, and 0.0 (light blue spots) at the frequency between 50/24 h and 60/24 t is represented for plant B1 at frequencies between 40/24 h and 50/24 h, and for plant D1 between 30/24 h and 40/24 h. If all time series are cut to the same length/duration, this difference disappears and the amplitude sequence (spots) is represented for all plants at the same frequency band. This drawback can be handled by unifying time series length or by using the continuous (instead of the discrete) version of WT (as done in this study). Important for the use of any of the methods for explorative purposes is the intended testing of different sets of parameter values (different resolutions, coefficients, levels) in order first to explore the abilities of the methods for the specific application, and second to detect potential misinterpretations because of methodological drawbacks of the methods. Finally, without any theoretical background or hypothesis regarding the actual (biological) processes behind, the interpretation of FA methods can be

misleading. The methods most intuitively comprehensible for persons not familiar with the mathematical background of the methods are MM and PP (as simple plot methods), and HHT (as data-based instead of theory-based method). Relevant pros and cons are summarized in table 4.1.

Table 4.1: Overview of frequency analysis methods applied in this study [KS19a]: Local minima and maxima (MM), Phase portrait (PP), Cepstrum (CEP), Short term Fourier transform (STFT), Wavelet transform (WT), Stockwell transform (ST), Hilbert-Huang transform (HHT)

Method	Target	Pros	Cons
MM	Visualize oscillation rhythms	Easily plotted, first insight into regularities	Qualitative, not a FA method in a narrow sense
PP	Visualize regularities of dynamic behavior	Easily plotted, first insights into dynamics	Qualitative, not a FA method in a narrow sense
CEP	Detect sideband	Detection of periodic signal components	Only frequencies of same amplitude are shown as sideband, qualitative ‘peak’ interpretation
STFT	Detect transient variations in frequency spectrum	Approved standard tool for FA in different applications	Restricted resolution for time or frequency, not optimal for signals of different time and frequency spectra within the same signal
WT	Analyze frequencies of different lengths for general signal pattern recognition	Simultaneous representation of different frequency spectra and time resolutions	Limited representation of amplitudes, discrete WT: difficult comparison of time series of different lengths
ST	Detect transient variations in frequency spectrum	Enhanced STFT method: combination of high time with high frequency resolution plus amplitudes	High computational requirements for big data, comparably new method (applications still tested), comparison of time series of different lengths
HHT	Detect concealed physical relations/ disturbance-initiated natural oscillations	Distinction of different frequencies into time series, comprehensible interpretation	Not theory-based (empirical), comparably new method (applications still tested)

In this study, all named methods are applied to the data to analyze as much as possible unknown features of the measured data and to explore the explanatory power of the different methods for leaf temperature behavior. For application, these methods are available in the form of toolboxes for analysis software. To perform the numerical results, the signal processing Toolbox of Matlab (Mathworks ©) was used.

4.4 Frequency analysis results

4.4.1 Hypotheses

Derived from the above cited studies on stomatal oscillation behavior, the expected results of the frequency analysis are:

Hypothesis 1 (H1):

Water deficit results in transpiration reduction because of stomatal closure and hence in rising leaf temperatures [JIRPJ81] [Jon07] [MS12]. This can be expressed by

$$A_S > A_{FI},$$

with A_S denoting oscillation amplitude A of plants in the state “water stressed”, and A_{FI} denoting oscillation amplitude A of plants in the state “non-water stressed”.

Restrictively, considering the superimposed transpiration oscillation amplitudes due to stomatal oscillations as investigated for oat plants e.g. in [BJK74], the amplitudes can show another behavior: The stepwise reduction of water potential in the root medium resulted initially (at mild stress) in a reduced transpiration oscillation amplitude, and finally (at high stress) to an immediate stop of oscillation activity. As the wavelength was not affected by the treatment in this experiment, the transpiration rate amplitude reduction is based on a reduction of stomatal conductivity, e.g. by reduced stomatal opening width. This result is in accordance with the a.m. hypothesis 1, as reduced transpiration results in an expected leaf temperature rise. However, the investigation of leaf temperature frequency behavior can show superimposed oscillations with opposite amplitude behavior.

Hypothesis 2 (H2):

Water deficit results in stomatal oscillation (start condition) and hence in leaf temperature oscillation [Ape67] [ZRS⁺10] [WdCRM10]. This can be expressed by

$$F_S > F_{FI},$$

with F_S denoting oscillation frequency F of plants in the state “water stressed”, and F_{FI} denoting oscillation frequency of plants in the state “non-water stressed”.

As described above, this specific oscillation start behavior is not observed in all experiments of the a.m. studies. However, in [BJK74] the application of abrupt root medium water potential reduction pulses resulted in transpiration oscillation phase shifts due to hydro-passive stomatal openings. Phase shift and amplitude value were altered depending on pulse duration and phase position at pulse start. Therefore, at least hydro-passive openings due to water stress incipience can also result in measurable frequency alterations and can hence be detectable by standard FA methods.

4.4.2 Local Minima and Maxima (MM)

In figure 4.3 the results of the MM are presented. Here, the measured local maxima (attributed to stomatal opening and resulting in leaf temperature decrease) and local minima (attributed to stomatal closure and resulting in leaf temperature increase) for the plants A1, B1, C1, and D1 are depicted. These local extrema represent the inflection points at which the leaf temperatures switch from decreasing values to increasing values (or vice versa). This means, only the respectively smallest measured value before a temperature rise and the respectively highest measured value before a temperature decrease are depicted in the diagram.

The connecting lines between the axis of abscissae and the particular signal values denote the events of stomatal opening/closing. Hence, the lines' sequences denote the oscillation rhythms: The higher the density of lines, the higher the stomatal activity (opening/closing) is. It was expected to observe a distinct change in oscillation rhythms of stressed plants compared to fully irrigated plants (cf. hypothesis 2).

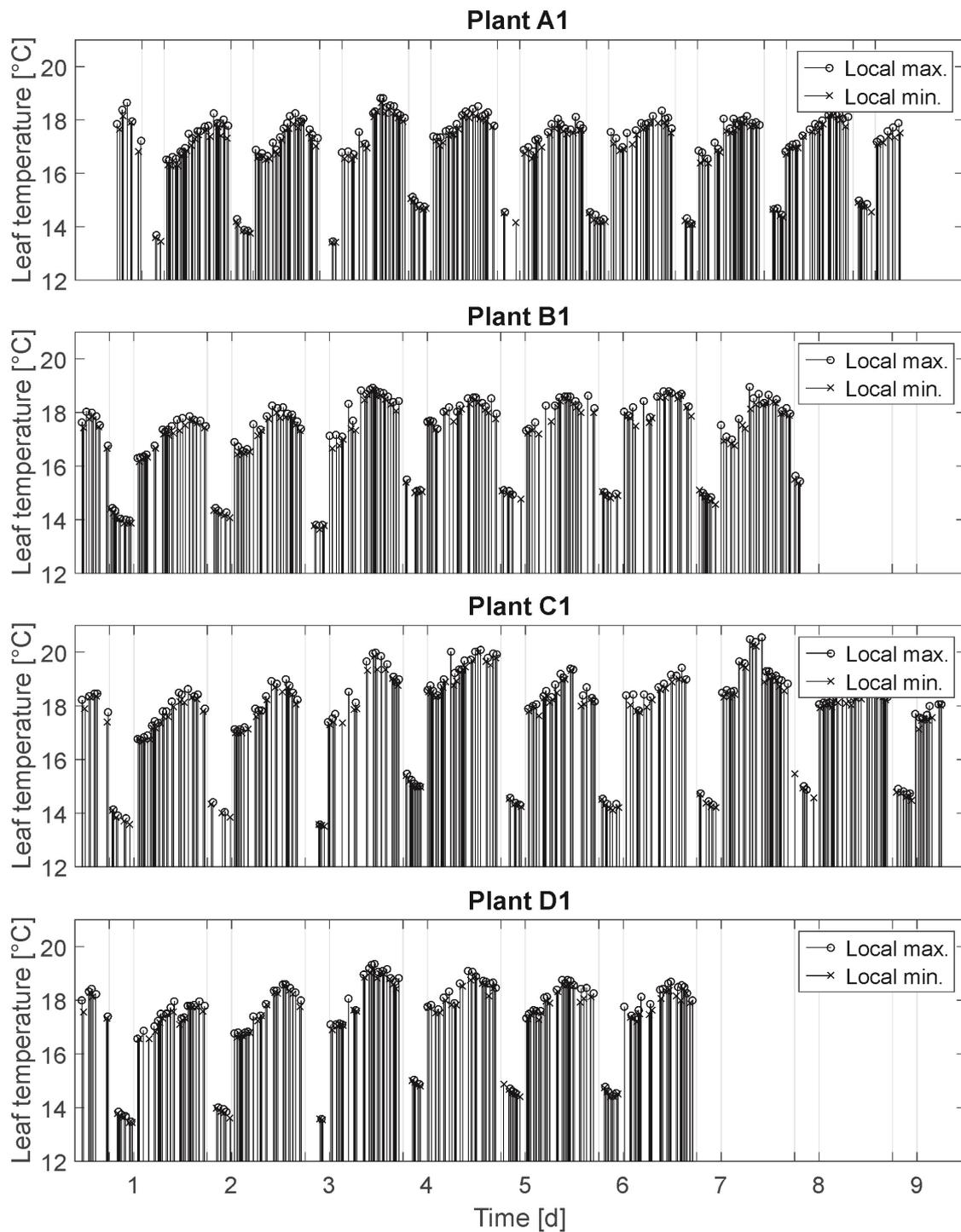


Figure 4.3: Local minima and maxima of plants A1, B1, C1, and D1 [KS19a]: Lines between the x-axis and the signal values denote the events of stomatal opening/closing: Local maxima are attributed to stomatal opening, local minima are attributed to stomatal closure.

Selected results are:

- Leaf temperature oscillation is measured for all plants during daytime as well as at nights independent of irrigation treatment.
- Different leaf temperature oscillation rhythms, denoted as periods of
 - Very high oscillation activity (extremum/inflection point at each measurement (which can be qualitatively detected independent from sampling rates)),
 - Regular and lower oscillation (about one local extremum/h), and
 - No oscillation for more than one hour (rest period), are found for all plants independent of irrigation treatment.
- Leaf temperature oscillation rest periods are regularly, but not only detected for the nights and measured for all plants independent of irrigation treatment. These rest periods often start (>50 %) before illumination is switched off.

Summarizing, the analysis of MM does not support the hypothesis 2, that a water deficit is a start condition for stomatal oscillation.

4.4.3 Phase Portrait (PP)

The results of the PP are presented for the same plants A1, B1, C1, and D1 (figure 4.4). On the x-axis the state variable leaf temperature and on the y-axis the first derivative (leaf temperature change rate between each measurement, $\Delta t = 20$ minutes) are plotted. Each measurement value is represented by a node. The nodes are connected by edges resulting in a (angular) curve. The plotted measurements depict the oscillations by moving in a circle turning clockwise. Different colors denote different daily cycles. For example, the night temperature oscillates in small steps of about 0.1 °C decreasing for about 2 degrees per night (15.5 °C to 13.5 °C). When light is switched on, the temperature values “jump” from the lowest night value of the respective day in about 2 - 4 measurements (nodes) to the lowest respective daily value at about 17 °C (end node at the descending edges of the upper circles).

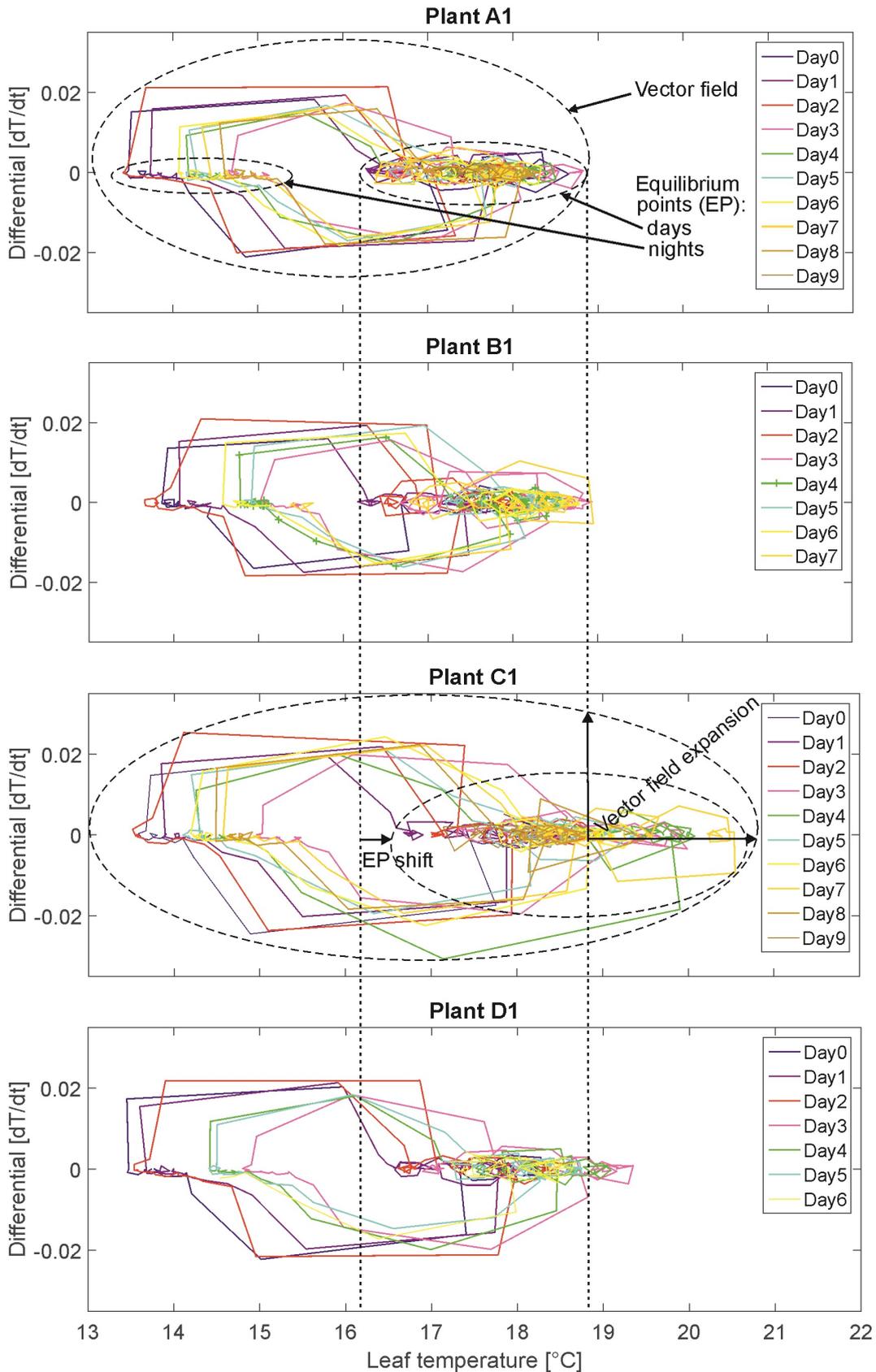


Figure 4.4: Phase Portrait of plants A1, B1, C1, and D1 [KS19a]: Measurements are plotted in circles turning clockwise. Plant C1: Vector field (large dashed oval) extension and shift of equilibrium point (small dashed oval) compared to plant A1.

Two equilibria (or: areas of attraction) are depicted, denoting temperature ranges during daytime (accumulation/queue of small circles e.g. for plant A1 at temperatures between 16 °C and 19 °C) and at night (accumulation/queue of very small circles e.g. for plant A1 at temperatures between 13,5 °C and 15,5 °C). These two equilibria for the values during daytime and the values at night are illustrated by the two smaller, broken-lined ovals in the PP of plant A1 and exemplary also for plant C1. Plant C1 (high stress) shows a shift of the equilibrium point in the days towards higher leaf temperatures. The vector field is illustrated exemplary by the large, broken-lined oval in the PP of plant A1 and C1 representing the totality of all measured leaf temperature values for the particular plant. Here, the vector field of plant C1 is extended compared to the one of plant A1. The value of the leaf temperature change rate denotes the speed of temperature changes between two measurements. It was expected to observe a vector field extension (additional, higher leaf temperatures and change rates) for stressed plants compared to fully irrigated plants (cf. hypothesis 1).

Selected results are:

- Overall leaf temperature ranges during daytime are higher for plants in states “water stresses” (16.0 - 22.0 °C) than for plants in state “non-water stressed”: (16.0 - 19.5 °C). This means, that stressed plants produce higher total leaf temperatures. But, leaf temperatures of highly water stressed plants exceeding the maximum leaf temperature of 20 °C (maximum leaf temperature of well-watered plants) are detected only for 2 plants. This result does not support hypothesis 1 unambiguously.
- Maximum plant individual heating up during daytime (lowest to highest daily temperature value (δ LT) is higher for plants in state “water stressed” (1.5 - 4.0 °C) than for plants in state “non-water stressed” (1.0 - 2.5 °C). But, maximum plant individual heating up during daytime of highly water stressed plants of more than 2.5 °C (maximum value of well-watered plants) are detected only for 3 plants (group C). Also this result does not support hypothesis 1 unambiguously.
- Overall cooling down ranges of leaf temperatures at night range for all plants between 0.5 - 1.5 °C independent of irrigation treatment. In this experiment, water regime is not influencing the cooling amplitude during night.
- Cooling down of leaf temperatures during daytime before switch-off of illumination is slightly higher for plants in state “water stressed” (0.5 - 1.5 °C; two highly stressed plants of group C: 2.0 °C) than for plants in state “non-water stressed” (0.5 - 1.0 °C). This again supports hypothesis 1.

Summarizing, the analysis of PP does not generally support the hypothesis 1, that a water deficit acts as a condition for stomatal oscillation amplitude rise.

4.4.4 Cepstrum (CEP)

The results of the CEP are presented for plants A1, B1, C1, and D1 (figure 4.5). On the x-axis the so-called quefrequency is plotted, representing a periodic time interval of redundant signal components. On the y-axis a dimensionless coefficient representing the existence/non-existence of a sideband (periodic components) of individual frequencies is plotted. For example, the quefrequency of 1.0 corresponds to the period of 1 d (24 h). In the plot of plant A1 a peak with the y-value of 0.6 is shown at a quefrequency of 1 d. This represents the 24 h-light-darkness rhythm in this experiment. The peak is not as conspicuous as expected, knowing that the 24 h-sideband is artificial and very precise in period duration. This is due to the plant individual diurnal variations in leaf temperature amplitudes (cf. 4.2: e. g. oscillation at a period duration of 3 - 4 days with amplitudes of 1 - 2 °C in the days). The CEP method only considers quefrequencies of similar amplitudes being part of a sideband. Whereas, well-watered plants like A1 still show a significant peak at quefrequency 1.0 (approximately 3-fold of the neighboring values) all other plants do not show the 24 h-sideband because of the variation in diurnal temperature amplitudes despite the precisely equal period duration.

Amplitudes are not particularly plotted in CEP, but as only repetitive amplitudes of similar values are considered to be part of the sideband, a variance in amplitudes is detectable by a nonexistence of considerable peaks. Here, “considerable” is only defined qualitatively: “considerable” denotes, that the peak has to be more than double to three times higher than the ambient peaks in order to be significant. Here, according to the Shannon-Nyquist-Theorem all quefrequencies higher than 0.03 are reliable (cutting edge frequency of 36/24 h). A variation of the quefrequency resolution (e. g. towards higher quefrequencies than 1.5) did not show particular results. This could be different if the experiments duration would be extended to detect oscillations of longer period durations. The large number of high peaks at quefrequencies below 0.3 partially result from an ‘unclean’ resolution at these quefrequencies. A variation of resolution towards smaller quefrequencies did not show significant results. However, it was expected to observe a distinct sideband displacement for stressed plants compared to fully irrigated plants representing higher frequencies.

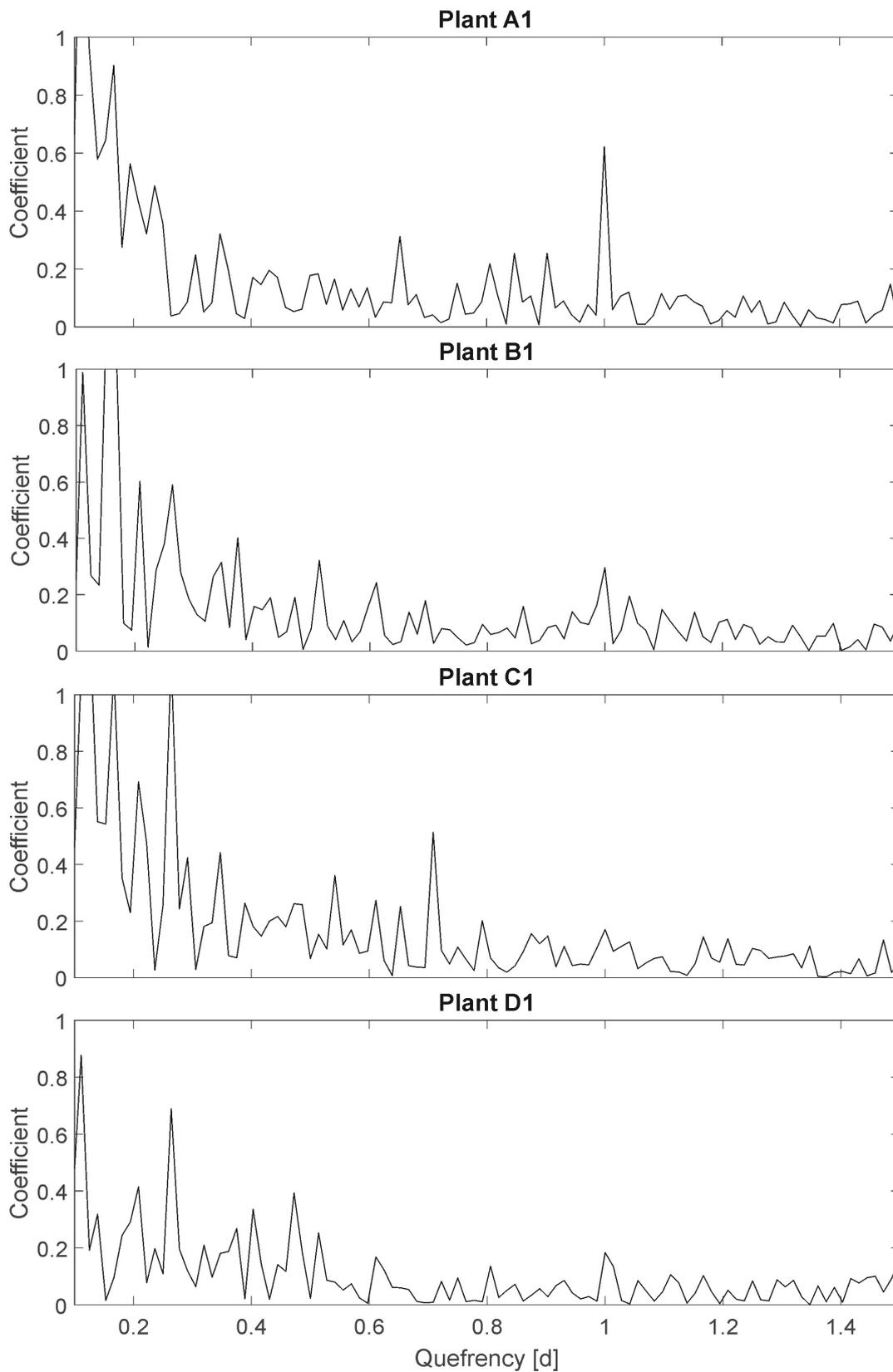


Figure 4.5: Cepstrum of plants A1, B1, C1, and D1 [KS19a]: Quefrequency denotes a periodic time interval, coefficient (dimensionless) denotes the echo of a specific frequency.

Selected results are:

- The peak at quefrequency 1.0 represents the known day-night-rhythm and is considerable for plants in group A (well-watered, peak > 0.4), less significant for plants in group B (mild stress, $0.2 < \text{peak} < 0.4$), and even less significant for plants in group C (high stress, peak < 0.2). This can be interpreted as an increasing difference in amplitude in time resulting from leaf temperature increases for stressed plants (cf. PP). On the other hand, plants in group D (not at all irrigated) show peak values at a quefrequency of 1.0 between 1.8 (D1, very uniform amplitude) and 0.4 (D2, D3; comparable to group B). The result is therefore not unambiguous related to hypothesis 1.
- The peak at quefrequency 0.25 represents a periodic frequency component every 6 hours: about 60 percent of all plants independent of irrigation treatment have a peak higher than 0.6 at this quefrequency (in 4.5 only represented for plants B1, C1, and D1). The ambient peaks are also comparatively high; therefore, this peak is assumed to be of no relevance. However, as it relates to all plants, irrigation treatment is not relevant for this sideband and also not for hypothesis 1.
- Additional peaks with coefficients higher than 0.4 are detectable at quefrequency 0.5 for plant B2 and B5 (mild stress), and at quefrequency 0.7 for plant C1 (high stress), indicating periodic components at that period duration. The information cannot support hypothesis 2 (sideband displacement due to higher or additional frequencies), as no additional peaks for all other plants can be detected.

Summarizing, the results of the CEP analysis do not unambiguously support the hypotheses.

4.4.5 Short Term Fourier Transform (STFT)

The results of the STFT are presented for plants A1, B1, C1, and D1 (figure 4.6). On the x-axis the time and on the y-axis the frequency are plotted. The spectrum at the right side denotes the amplitudes of oscillations. Here, amplitudes of up to 21 °C are depicted, representing the total, measured leaf temperatures. It was expected to observe a distinct frequency spectrum change for stressed plants compared to fully irrigated plants.

Applying STFT the day-night-cycle can be clearly depicted with regular amplitude alterations of approximately 16 - 20 °C, which is in accordance with the PP results.

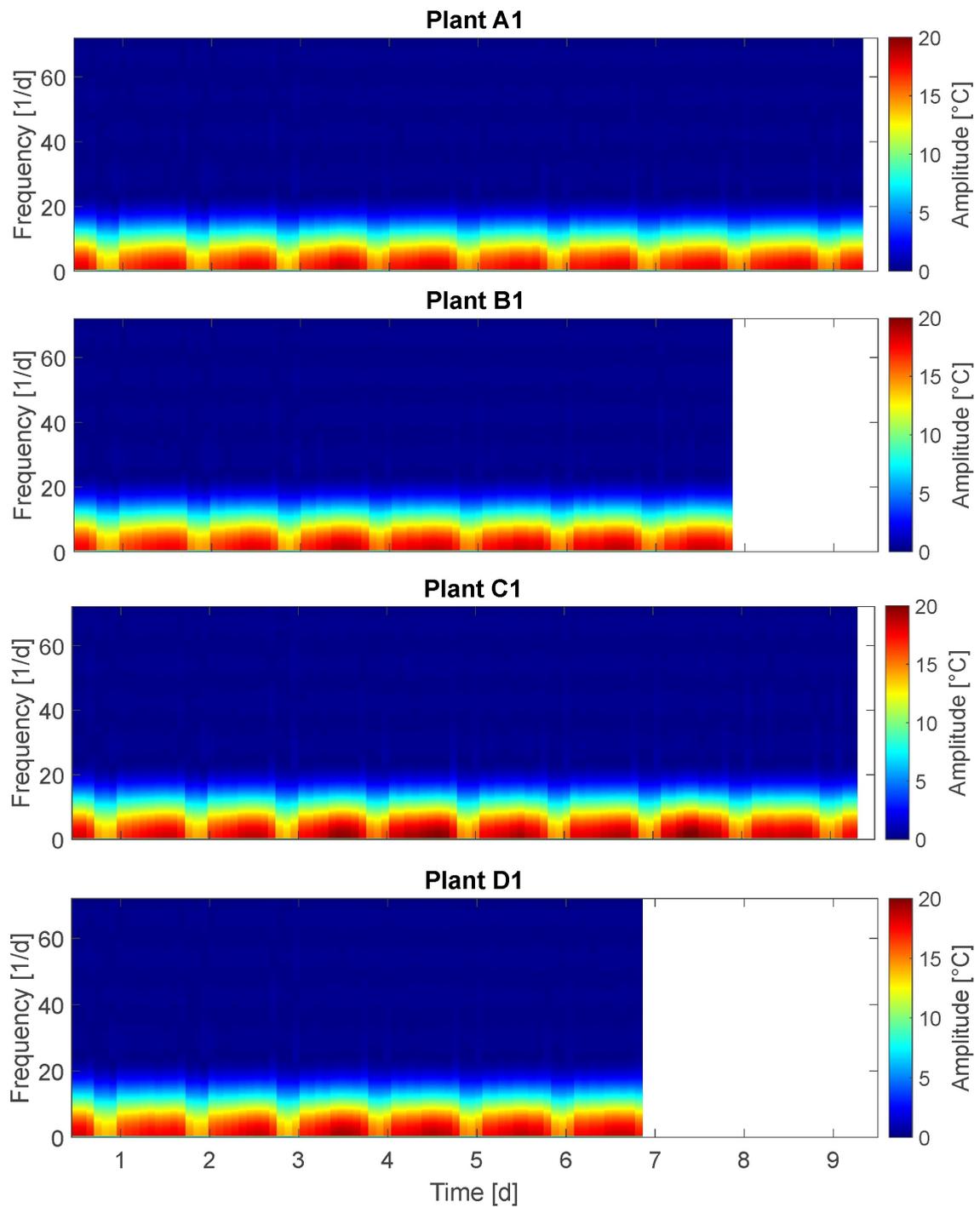


Figure 4.6: Short Term Fourier Transform of plants A1, B1, C1, and D1 [KS19a]: Time-frequency-energy-representation of leaf temperature courses

At frequencies from 1 - 5/24 h the amplitude exceeds 18 °C, for plants A1, B1, and D1 only at middays, whilst for plant C1 frequency and duration of maximal amplitude are higher. A water deficit-based behavioral change expected at frequencies of 24/24 h and more could not be detected.

Selected results are:

- Non-water stressed plants show amplitudes exceeding 18 °C at frequencies of 1 - 5/24h only at middays, whereas later stressed plants show these higher leaf temperature amplitudes also in mornings. This supports hypothesis 1. On the other hand, only in one group (C) this behavior was detected. This limits the significance of the result.
- No difference in frequencies for amplitudes between 1 °C and 20 °C are observed for all plants irrespective of irrigation treatment.

Summarizing, the STFT analysis also does not support the hypotheses.

4.4.6 Wavelet Transform (WT)

The results of the WT are presented for plants A1, B1, C1, and D1 (figure 4.7). On the x-axis the time and on the y-axis the model-based frequency levels are plotted. Here, seven frequency levels are given. The spectrum at the right side denotes a coefficient representing the amplitudes of oscillations. Although the coefficient scale of 0 - 100 does not represent real amplitudes, high coefficient values are attributed also to high amplitudes. A direct conversion of the coefficient into amplitudes is not possible.

Within the wavelet transformed results, ‘time blocks’ of approximately equal time durations are depicted at each frequency level: Here, the width of the blocks/segments of a higher frequency level are an integer multiple of the width of the next lower frequency level. This represents the model-based modified time resolution on behalf of a higher frequency resolution in the respective level. The ranges of time are determined by the WT according to the given data and the number of levels chosen. Therefore, the day-night-cycle is not exactly met at any of the levels but located between level 5 and 6. The adjustment options for WT diagrams relate to the (amplitude-related) coefficient and the number of levels (time resolutions). Therefore, the interpretation of WT for this application is not as comprehensible as e.g. of the STFT.

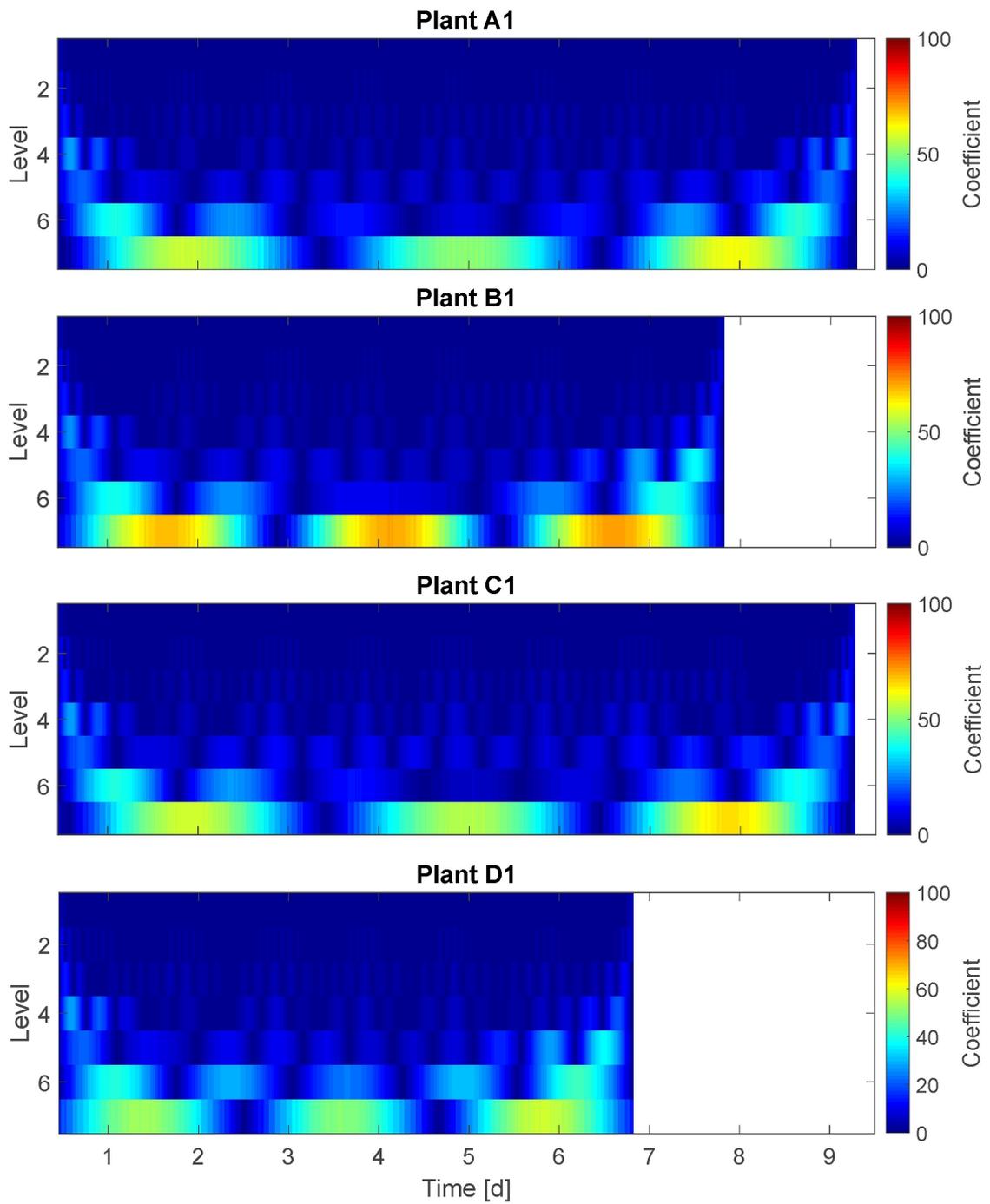


Figure 4.7: Wavelet Transform of plants A1, B1, C1, and D1 [KS19a]: Seven model-based frequency levels, the coefficient representing amplitudes of oscillations

In the shown WT-result each frequency level is textured in approximately symmetric, regular amplitude segments of time durations between 2 h (Level 2) and 72 h (3 days) (Level 7) with

- amplitude coefficient of up to 30 on the higher frequency levels 1 to 5,
- amplitude coefficient of up to 55 on the frequency level 6, and
- amplitude coefficient of up to 100 on the lowest frequency level 7.

This means for example for plant C1 that the segments on level 6 have approximately the 2.5-fold duration of the segments on level 5, and the segments on level 5 have approximately the 1.25-fold duration of the segments on level 4. Here, plant B1 is an exception: at frequency level 6 plant B1 has one nearly double sized segment between day 3 and day 5. This indicates a higher amplitude coefficient at day 4 compared to other days (and plants). Conspicuous changes in frequency or amplitudes at moments in time for which it is known that plants experiences water stress cannot be detected.

It was expected to observe a distinct frequency spectrum change for stressed plants compared to fully irrigated plants. Selected results are:

- At level 6 (Time window width: 1.5 days) the amplitude coefficient of highly stressed plants is higher (55-60) compared to well-watered or mildly stressed plants (about 40). This supports the hypothesis of higher amplitudes at least for highly stressed plants.
- On the other hand, the amplitude coefficient is maximal for all plants at level 7 (60-100), but the plants in the group without any irrigation reached just the coefficient level of the mildly stressed plants, or even well-watered ones. This does not support hypothesis 1.

Summarizing, based on the WT-graphs no distinct frequency spectrum can be identified.

4.4.7 Stockwell Transform (ST)

The results of the ST are presented for plants A1, B1, C1, and D1 (figure 4.8). On the x-axis the time and on the y-axis the frequency is plotted. Maximum frequency is $72/24$ h, equaling the sampling rate. The spectrum at the right side represents the amplitudes of oscillations.

Here, the small amplitudes of $0.0 - 1.2$ °C are selected according to the specific ability of ST to analyze higher frequencies. This is also the reason, why the day-night-cycle is not detectable: As the leaf temperature amplitude changes due to the light-on/light-of-cycle amounts to $3 - 4$ °C amplitudes, these events are not represented in this diagram. According to the Shannon-Nyquist-Theorem only the measured frequencies below $36/24$ h are considered in the following observations. It was expected to observe a distinct frequency spectrum change for stressed plants compared to fully irrigated plants.

In ST continuous amplitudes and alternating amplitudes can be detected. For example, at a frequency of $8 - 10/24$ h a continuous amplitude of approximately 0.8 °C for groups A, B, and D, and of approximately 1.2 °C for group C is depicted. This is in accordance with the observation, that the maximum daily amplitudes are observed in group C. Further, at frequency $18 - 22/24$ h an alternating amplitude between the values of $0.1 - 0.5$ °C in a daily rhythm is observable for all plants. Deduced from the above cited studies on water deficit-related stomatal oscillations, a water deficit-based behavioral change would be expected at frequencies of $24/24$ h and more. This could not be observed for any of the plants in this experiment.

Selected results are:

- Amplitudes at frequencies of $8 - 10/24$ h are 50 % higher (up to 1.2 °C) for highly stressed plants compared to non-water stressed ones. On the other hand, this is only observed for 50 % of the highly stressed plants. This does not support the hypothesis 1 unambiguously.
- The expected higher frequencies at amplitudes of $0.1 - 1.2$ °C for highly stressed plants could not be observed, also not for any plant irrespective of irrigation treatment. This does not support hypothesis 2.

Summarizing, the results of ST analysis do not support hypothesis 2; and hypothesis 1 is only partly supported.

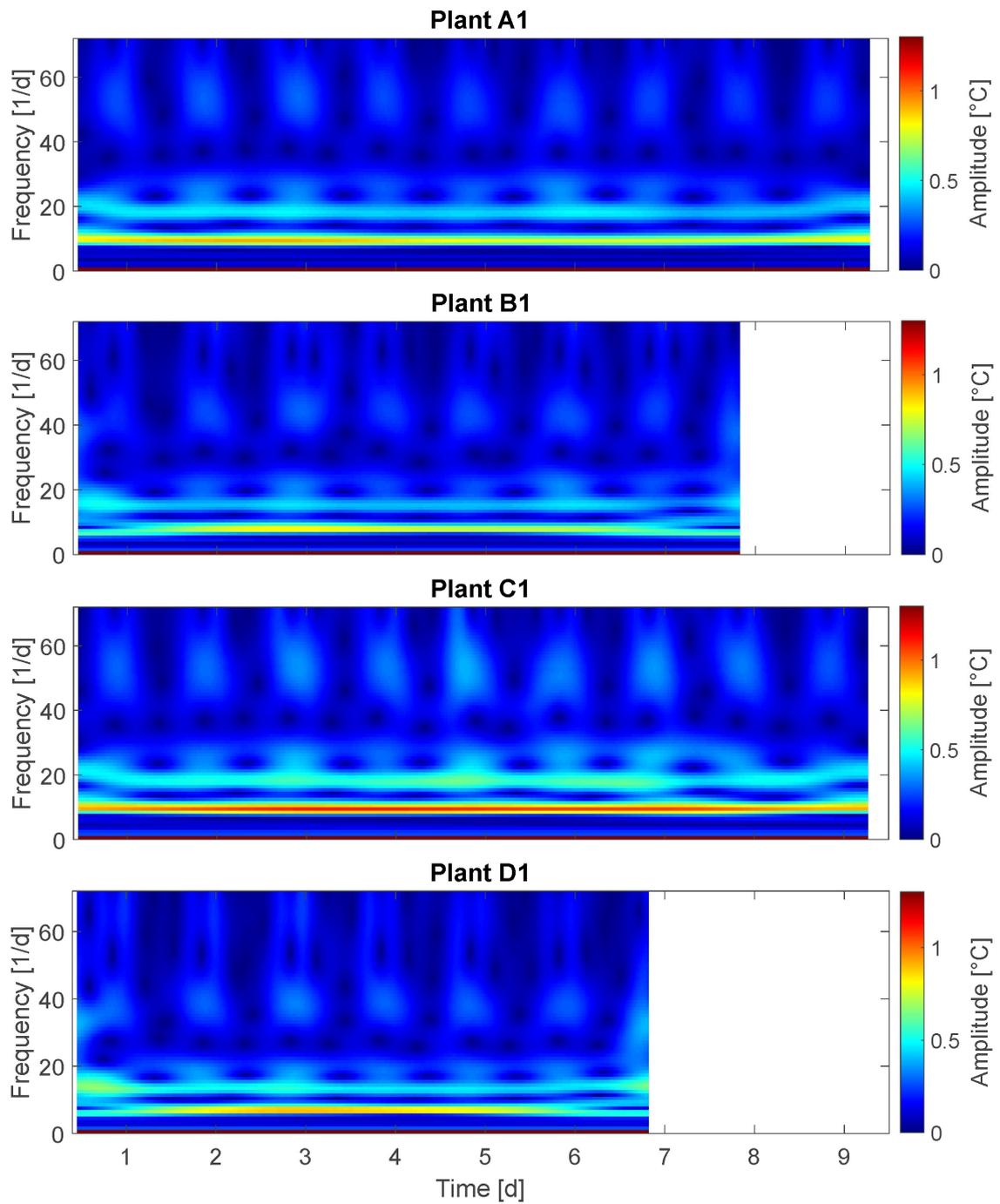


Figure 4.8: Stockwell Transform of plants A1, B1, C1, and D1 [KS19a]: Time-frequency-energy-representation of leaf temperature courses

4.4.8 Hilbert-Huang Transform (HHT)

The results of the HHT are presented for plants A1, B1, C1, and D1 (figure 4.9). The frequency spectrum is depicted in a set of curves, so called IMFs. For each IMF (frequency) on the x-axis the time and on the y-axis the amplitude are plotted. The lowest IMF in each case defines the stop-function of the algorithm and does not represent a frequency. The stop-function can be selected from a set of options. Here, the so-called S number criterion [HWL16] is chosen, stopping the algorithm if for a number of consecutive siftings (loops) the number of extrema and zero-crossings stay the same (or plus one). It was expected to observe a higher number of IMFs and/or IMF time behavior changes for stressed plants compared to fully irrigated plants.

In HHT the total number of IMFs per plant represents the number of different frequencies identified in the leaf temperature time behavior as

- Group A (FI): Two plants have 9 IMFs, all others have 8 IMFs,
- Group B (MS): All plants have 8 IMFs,
- Group C (HS): Two plants have 7 IMFs, all others have 8 IMFs, and
- Group D (NI): Three plants have 7 IMFs, all others have 8 IMFs.

The general conclusion, that water deficit results in a smaller number of IMFs cannot be drawn, as plants with 7 IMFs also died earlier in the experiment, resulting in a shorter time series. However, plant A1 (and A3, not shown here) has 9 IMFs compared to other plants of equal life time and only 8 IMFs. Here, an additional frequency is detected.

Further, HHT based on the total time series (10 days) results in two more IMFs than HHT based on split single-day time series composed to the 10-day period (not shown here). This indicates superimposed multi-day frequencies.

Results based on IMF analysis can be stated as follows:

- In IMF1 the light-darkness oscillation at amplitudes below 5 °C can be detected for all plants.
- In IMF2 an obviously day-night-based oscillation at amplitudes below 5 °C can be detected. This oscillation is not exactly aligned to the light-darkness cycle. The related behavior can be observed for all plants.

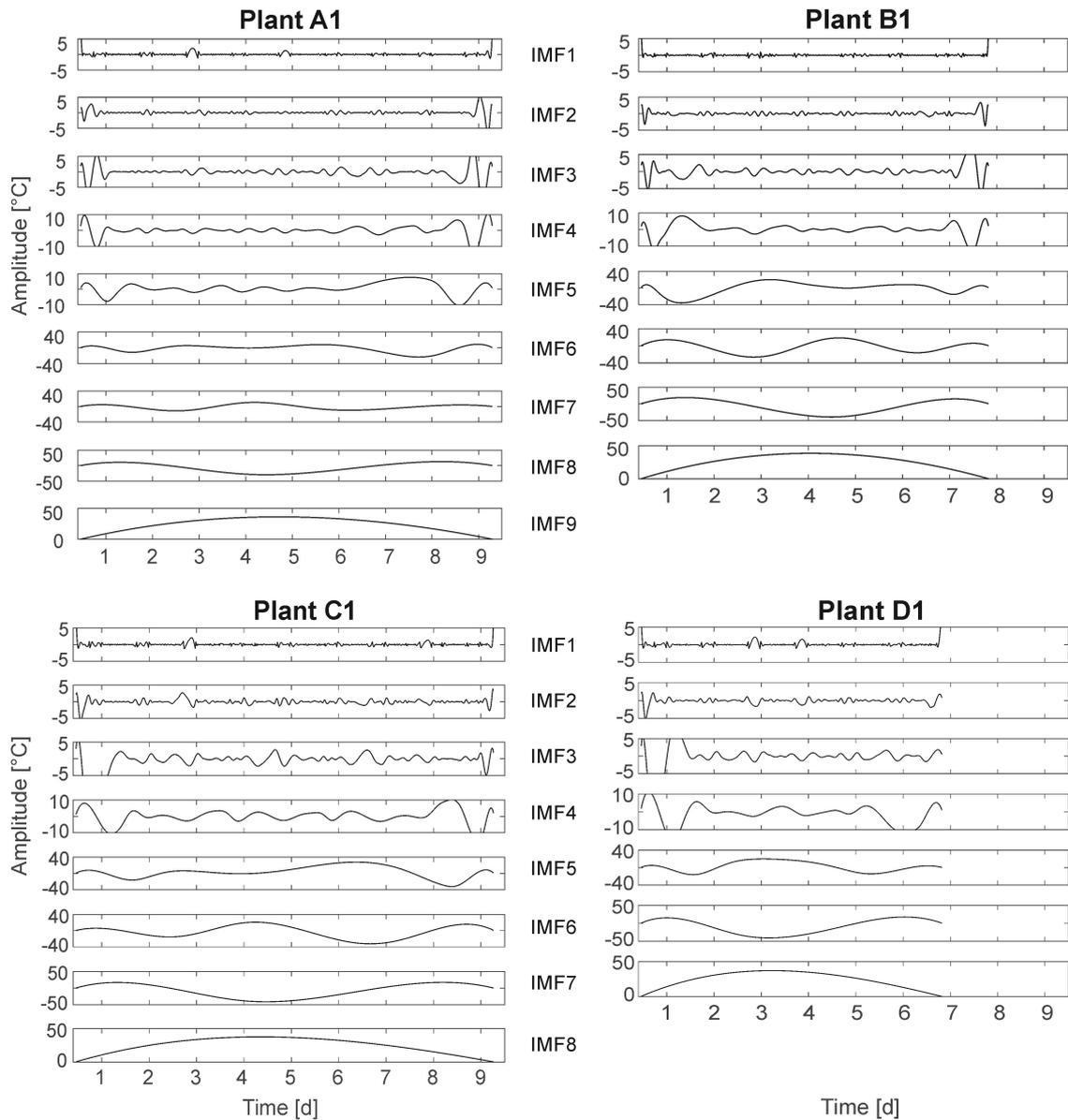


Figure 4.9: Hilbert-Huang Transform of plants A1, B1, C1, and D1 [KS19a]: Frequency spectrum depicted in a set of curves (IMFs) with time on the x-axis and amplitude on the y-axis

- In IMF3 and IMF4 (for A1 and A3 also partly in IMF5) oscillations of frequencies higher than $1/24$ h are depicted. The amplitudes are below 10 °C (IMF3) and below 20 °C (IMF4, for A1, A3: IMF5).
- In IMF5, IMF6, and IMF7 (A1 and A3: IMF6, IMF7, IMF8) oscillations show frequencies of less than $1/24$ h (multi-day frequencies). The amplitudes are given with up to 40 °C. The maximum leaf temperatures are obviously depicted in IMF6 (A1/A3: IMF7). For example, plant C1: maximum leaf temperatures appear at days $4/5$ and 8 (cf. 4.2. This can be detected in IMF6).
- It should be noted, that in HHT amplitudes of up to 50 °C are depicted. These high temperature values are not real values in terms of surrounding air temperature, but are a result of the specific algorithm used in HHT. Here, amplitudes larger than the natural temperature variations represent superimposed vibrations of the signal of lower frequencies hidden in the temperature signal and therefore depicted in °C.

Comparing the HHT of the four plants with different irrigation treatments the symmetry in IMF5 is remarkably different: The fully irrigated plant (A1) has a plateau of about 20 °C amplitude between the days 2 and 6. This plateau is compressed to an elevation for the not-irrigated plant (D1), as well at an amplitude of 20 °C, probably because of the shorter life time. This symmetry is not present for plants B1 (MS) (Elevation on the left: earlier, higher amplitude up to 20 °C) and C1 (HS) (Elevation on the right: later, higher amplitude up to 20 °C). This observation cannot be ascertained for all plants in each group, but

- The number of symmetric IMF5 (A1/A3: IMF6) is highest in group A (3 plants), lowest in group C (1 plant),
- IMF5 in group B is only symmetric or with an elevation on the left,
- IMF5 in group C is only symmetric or with an elevation on the right.

On the other hand, elevations on both sides, right or left, are both found also in the groups A (FI) and D (NI). Selected results are:

- Contrary to hypothesis 2, the number of IMFs (frequencies) is rather higher for fully irrigated plants than for stressed plants. This is not only due to a longer lifetime, as also plants from groups B and C survived the complete experiment.
- A distinct shift/change in IMF time behavior for stressed plants can also not unambiguously be detected, just as an increase in amplitudes. This result does not support hypothesis 1.

- At least one of the detected frequencies (day-night-cycle) is not plant-based.

Summarizing, the results of HHT do not support the hypotheses. A further investigation of the reason for the appearance of the different IMFs is recommended.

4.5 Summary and discussion

The above described findings of the different explorative frequency analysis methods are recapped in table 4.2. The results do not unambiguously support the hypotheses, that leaf temperature amplitude (H1) and frequency (H2) of plants in water stressed states are generally higher than those of plants in well-watered states. This at first sight unsatisfactory result retrieves a number of interesting observations and questions:

Leaf temperature variability: A higher amplitude (H1) for stressed plants was detected, but not for all stressed plants. One reason for this result can be, that the variability of leaf temperatures is already high (3 °C, 16.5 - 19.5 °C) between all plants at well-watered state at the beginning of the experiment (Day 1). As the experiment progressed, the variability of well-watered plants remains between 2.0 - 2.5 °C (16.5 - 19.0 °C in the days) during the entire experiment, whereas the variability in mildly stressed plants (groups B, C, and D at day 1.5 - 2.5) increases to 3.5 °C (16.5 - 20 °C in the days), and in highly stressed plants (Groups C and D at day 2.5 - 3.5) to 5.0 °C (17.0 - 22.0 °C in the days). However, only three highly stressed plants of groups C and D exceeded the maximum variability value of 2.5 °C (maximum value of well-watered plants). Restrictively, the generalization of single-point leaf temperature measurements to whole leaf temperatures and hence to whole leaf transpiration is not possible, as stomata do not show in all cases synchronized behavior [PFJ03b]. However, based on the assumed causality between plant water stress and transpiration rate/leaf temperature and as about 1890 single measurements of highly stressed plants were taken during this experiment, the rate of highly stressed plants with distinct leaf temperature elevations could be expected to be higher than 30 %. This means in practice that under constant and equal environmental conditions one objectively well-watered plant with a leaf temperature of 17.5 °C is compared to an objectively highly stressed plant of equally 17.5 °C leaf temperature.

Table 4.2: Frequency analysis results for leaf temperature (LT) measurements of water stressed maize plants compared to full-irrigated plants [KS19a] (Abbr.: Local minima and maxima (MM), Phase portrait (PP), Cepstrum (CEP), Short term Fourier transform (STFT), Wavelet transform (WT), Stockwell transform (ST), Hilbert-Huang transform (HHT), Hypothesis 1 (H1), Hypothesis 2 (H2), amplitude (A), frequency (F), full irrigated (FI), stressed (S))

* : Values of 50 °C are not representing real leaf temperatures, but result from the specific algorithm used in HHT.

Method	Expectation	Frequency	Amplitude	Observations	H1 $\mathbf{A}_S > \mathbf{A}_{FI}$	H2 $\mathbf{F}_S > \mathbf{F}_{FI}$
MM	Oscillation rhythm change	Not specified	12 - 21 °C	All plants: oscillations, rest periods, stressed plants: oscillation rhythms not higher	Not tested	Not supported
PP	Vector field expansion	Not specified	12 - 21 °C	Stressed plants: 30% showed higher max. LT, 15% higher daily warm-up, 50% higher pre-nocturnal cool-down. All plants: Equal nocturnal cool-down	Not unique	Not tested
CEP	Sideband displacement	0 - 1,5 (36 h) (sideband)	All amplitudes	Stressed plants: 75% showed less distinct peak at quefrequency 1.0, 40% additional peaks, no distinct difference in frequency shape.	Not unique	Not unique
STFT	Transient effect in frequency spectrum	0 - 72/24 h	0 - 20 °C	Stressed plants: 30% showed higher amplitude at frequency 1 - 5/d, no frequency spectrum change	Not unique	Not supported
WT	Transient effect in frequency spectrum	7 levels	Coefficient 100	Stressed plants: 25% showed higher amplitude coeff. at level 7, 50% higher amplitude coeff. at level 6, no frequency spectrum change	Not unique	Not supported
ST	Transient effect in frequency spectrum	0 - 72/24 h	0 - 1,4 °C	Stressed plants: 15% showed higher amplitude at frequency 8 - 10/d, no frequency spectrum change	Not unique	Not supported
HHT	More IMFs, IMF course changes	7 - 9 IMFs	0 - 50 °C*	Stressed plants: Number of IMFs not higher, no distinct IMF course change	Not supported	Not supported

The related research question is: Is leaf temperature per se representing the actual plant water supply status? or in detail: What is the detailed connection between the dynamical character of leaf temperature signal and water supply status? This question has implications on the use of leaf temperature signals for irrigation scheduling: Based on the presented results, plant individual absolute leaf temperature signals per se cannot be used for reliable irrigation scheduling. Instead, variability parameter of leaf temperature signals of canopies can serve as indicator for a general stress incipience. Here, stress-sensitive plants indicate water stress for all plants of a crop. This interpretation, of course, is restricted based on the presented results only to homogenous environmental conditions. However, the use of leaf temperature variability has been proposed by [CB82] based on field experiments.

Leaf temperature maintenance: The largest, plant-individually measured daily temperature rise under the presented conditions is 4 °C (plant C3, day 3, high water stress). This represents the potential minimum leaf temperature increase all highly stressed plants could physically have experienced. The smallest plant-individually measured daily temperature rise of objectively highly stressed plants under the presented conditions is 2 °C (plant D4, day 5, high water stress). This value is similar to the plant-individually measured daily temperature rise of well-watered (1.5 - 2.5 °C) or mildly stressed plants (1.5 - 2.0 °C). The resulting question is: How is a highly stressed plant able to maintain leaf temperature values comparable to those of well-watered ones? This result could be caused by open stomata despite wilting and minimum leaf water potential in stressed plants [Sch86]. Further, additional aspects despite pure hydraulic conductance considerations can also have an effect on plant water balance and hence transpiration and leaf temperature behavior [LTM⁺17].

Leaf temperature oscillation start condition: Further, a higher leaf temperature oscillation frequency of plants in water stress (H2) was not detected. Hence, the start-condition “water deficit” for an expected additional stomatal oscillation activity could not be measured under the presented experimental conditions. As desiccation is a continuous process, at least at some (mild) state of water deficit a frequency change was expected to occur, even if stomatal oscillation would stop in the course of further dehydration (high stress). Reasons could be:

- **Synchronized stomata:** Oscillation of transpiration and hence oscillation of leaf temperature can only be detected if stomata behave in a synchronized manner [Joh15]. This also applies to changes in oscillation behavior. An undetected change in oscillation frequency could therefore also result from unsynchronized stomatal behavior. However, this explanation would be in contradiction to the above mentioned assumption of a synchronized hydraulic signal controlling stomatal behavior.

- **Sampling rate:** At a sampling rate of 72/24 h, oscillations of a theoretical maximum cut-off frequency of 36/24 h can be detected. This represents the expected water deficit induced oscillation frequency described in literature. If the frequency induced by a water deficit is actually, significantly, and regularly higher than 36/24 h, the sampling rate of the existing measurements would not reliably detect variations in frequency. On the other hand, the probability is small that 14400 measuring points (20 plants, 10 days, 72/24 t sampling rate) are not sufficient to detect any changes in frequencies, as this would implicate that invariably all measuring points were taken in striking distance to the zero baseline of the water deficit induced oscillation. This is unlikely. However, further experiments are recommended utilizing higher sampling rates.
- **Causality transpiration to leaf temperature:** Water deficit-related stomatal oscillation does not necessarily result directly in leaf temperature oscillation. The causality between stomatal behavior under water deficit and leaf temperature behavior is based on the assumption, that stomatal opening results immediately in a leaf temperature decrease, and stomatal closing in a leaf temperature rise. In case this instantaneously resulting leaf temperature oscillation is damped or suppressed, e.g. by evaporation processes inside the leaf without direct transpiration effects (cf. [PHB10]), or additional cooling for example by IR-radiation (cf. [Cur36]), or influences of thermoregulation (cf. [BSHC97]), the expected leaf temperature oscillation is not directly detectable.
- **Measuring mistakes and measurement noise:** In principle, this may reduce informational value of the presented leaf temperature signals. Subsequent experiments (not yet completely evaluated) show similar results. Therefore, the measurements are assumed as not to be systematically wrong. Further, by applying standard frequency analysis methods the (always existing) measurement noise is systematically isolated/detectable. However, results still have to be validated and statistically ascertained.

Additional studies are necessary to ascertain and to further specify the characteristics of plant leaf temperature behavior. For example, based on the measured leaf temperature time series the HHT results in 6 - 8 superimposed oscillation frequencies per plant. The attribution of the single frequencies to physiological processes has to be further analyzed. Here, the distinction between plant system-based frequencies (e.g. autonomous stomatal oscillations) and environmentally induced frequencies (e.g. artificial day-night-cycle) should be particularly considered. Based on the presented results, a single plant-based identification of water stress based on the assumption of a water passive regulation of leaf temperature is not possible. The remarkable variability of the plants individual ability to regulate leaf temperature under severe water stress implicates considerably different water stress behaviors of plants within one cultivar.

However, the application of FA methods, particularly the Phase Portrait, the Hilbert-Huang-Transform, and the Stockwell Transform provide meaningful insights for the analysis of the presented data. Hence, the presented methods are generally applicable to data of this kind and origin. The selection of an adequate method should be based on considerations about the expected period lengths and frequencies, the required resolutions, computational aspects, and the target of the study. Important for the use of any of the methods for explorative purposes is the intended test of different sets of parameter values (different resolutions, coefficients, levels) in order first to explore the abilities of the methods for the specific application, and second to detect potential misinterpretations because of methodological drawbacks of the methods. Finally, for interpreting FA results theoretical background knowledge regarding the actual (biological) processes behind or hypothesis-based experiment design is required.

5 Summary, Conclusion, and Outlook

In this thesis a novel approach to implement irrigation is proposed. By integrating the plant system into the irrigation control loop the technical option to control growth by water input variation is accomplished. Further, by integrating a deficit irrigation model into the control approach the alignment of water inputs to actual plant necessities, and vice versa the alignment of plant growth to water availabilities is possible. Finally, the option to supervise water stress level developments by frequency analysis methods applied to leaf temperature data is examined.

5.1 Summary and conclusions

In the first part of the thesis (section 2) a comparative survey about existing soil-, plant-, and atmosphere-based irrigation methods is presented. The section is consistently structured according to system-theoretical taxonomy including the particular consideration of plant dynamic behavior in irrigation models. The results are briefly summarized in a causality mapping overview (figure 2.1) and in a model comparison overview (table 2.2). Conclusions of this analysis are:

Model of plant dynamic behavior: Practical state-of-art irrigation methods do not consider the productive portion of water stress (adaptive behavior), although deficit irrigation is tested in the fields. To date, mainly stress incipience is investigated for irrigation purposes disregarding plants' ability to cope with hostile conditions beyond stress incipience threshold. The expansion of existing irrigation methods by a suitable deficit irrigation model with variables for adaptive behavior and dysfunction due to water deficits is necessary to utilize this ability and to rise water use efficiency in irrigated agriculture.

Plant-based water stress detection: Broad scientific efforts are done to develop a plant-based monitoring of water stress. Numerous approaches are described using different variables (e.g. turgor, sap flow, transpiration) to observe plant water stress state. Here, the virtual output variable for agricultural production (growth or yield) is not considered as 'monitoring variable' neglecting the dynamics of the relevant input-output relation. Further, quantification of irrigation amounts is not (yet) possible based on plant system related stress measurements. Here, water availability (soil-based) or water consumption (atmosphere-based) measurements are the common solution. However, the plant-based approach for remote sensing of water stress most advanced regarding application in the field is leaf temperature measurement.

In the second part of the thesis (section 3) the development of a deficit irrigation model and the validation of the proposed control approach are presented. The model is realized as a state machine, describing dynamic plant behavior by states

which are interrelated by event-based transitions (figure 3.3). All realizable state trajectories are outlined in a Trellis-diagram (figure 3.4). In a test and training procedure (NSGA-II optimization) the model is parametrized and the open-loop control approach is validated by hypothesis testing. Results of this procedure are:

State machine model: Based on the experimental data and on the decision to divide the continuous desiccation process by the response and recuperation thresholds, three deficit irrigation relevant water stress states are determined: States S_1 , S_{1a} , and S_2 . By variation of the sequence of these states (training) different growth behavior is expected. Result is a growth behavior aligned with different control targets: growth (biomass), water use, and growth speed.

Open-loop control: Based on data analysis two major water-based growth performance ranges are determined: 'hydrological time'-based growth is the 'normal' growth behavior if plants do not experience any water stress and are also not trained (memory of stress events). 'Usage-bound' growth is the growth behavior induced by water stress incipience and which can be trained by repeated mild stresses. 'Usage-bound' growth is characterized by high correlation between water use (daily evapotranspiration rate) and growth rate, as opposed to a low correlation in 'hydrological time'-based growth. Hypothesis testing proved significance of state distinctions and behavioral differences. Further, a trend of accelerated leaf appearance due to a training with mild stresses was determined (cf. subsection 3.4.2).

Growth results: Comparing growth and water use performance variables of trained test groups (experiencing mild stresses) with corresponding control groups (constantly full irrigated) a substantially higher growth performance (+ 47 %) in trained (memorized) states is determined. A return to 'hydrological time'-based growth performance range with correspondingly lower growth performance is ascertained for a period of 3 days without training (repeated mild stress) (cf. table 3.7).

Concluding, training of plants with intended alterations of different water supply events (excluding high stress) improves water use efficiency and provides the option to control growth by water input trajectories.

In the third part of the thesis (section 4) the procedure of exploring the possibility to monitor plant water stress states by leaf temperature oscillation data is presented. An overview about different frequency analysis methods is given in table 4.1. Results of each analysis method are presented and an overview about the major findings are given in table 4.2. Conclusions derived from this procedure are:

Leaf temperature oscillation: Assumed stomatal opening oscillation change due to water stress could not be unambiguously proved by the implemented testings. However, analysis of frequencies and amplitudes resulted in a expansion of presumably different superimposed oscillations, not all of which are induced by environmental

conditions (e.g. illumination) (cf. Hilbert-Huang Transform in figure 4.9). Further investigations regarding source and meaning of these oscillations are proposed.

Frequency analysis methods: The applied frequency analysis methods are characterized by different strengths and limitations (cf. table 4.1). The use of these methods for analysis of the described experimental data showed differences in analytical power regarding this particular application. The methods most plausible for scientists not used to these methods are presumably Local Minima and Maxima (MM), Phase Portrait (PP), and Hilbert-Huang Transform (HHT).

Overall conclusion derived from this thesis project is the awareness that approaching disciplinary problems with the perception of a method-based area of expertise provides new ideas and solutions aside common paths. This relates to the state machine model as well as to plant growth control and to the application of frequency analysis methods in agricultural contexts. Reciprocal confrontation with disciplinary taxonomy and practices feeds back the findings generating unconventional approaches.

5.2 Outlook

For future work, the extension of the state machine model regarding minimum stress rest periods between mild stress events and a potential differentiation between training levels and targets can be included. The control approach could be tested for different control targets like endurance or load-bearing capacity. Plant-based stress level detection provides several options to proceed the works: Growth variable related stress measurement, automated IR-data extraction, further investigation of leaf temperature oscillation behaviors a.s.o. Finally, testing the presented approach under field conditions would provide further data to develop a concept for applicability in practice.

Further research is recommended to differentiate the proposed concept of positive stress regarding species/cultivars and developmental stages, and to extend the model by biomass partitioning aspects and water stress strategies of the various crops. The presented approach is still limited to one crop (maize), one cultivar (Ronaldinio, KWS), the very early vegetative stage (EC11 - 15), and leaf growth behavior under laboratory conditions (especially approximately constant temperature and constant humidity). Plant behavior caused by water deficits is a complex mechanism (cf. section 2.1) and assumed to be linked to different plant traits like plant height, leaf area, or biomass [MPD⁺11]. Detailed knowledge on the processes how stress signaling and developmental signaling is interrelated is still limited [MHZC17]. However, the trade-off between yield potential and drought resistance mechanisms is known, e.g. the redirection of sources from reproductive sink tissues [BPV16]. An intended water deficit treatment must therefore consider the specific stress strategy of the plants.

The presented experimental results support the proposed approach regarding the control of leaf growth as long as the critical stage (silking) has not been reached. Further research is recommended to differentiate the values for the response and recuperation thresholds regarding at least three developmental periods: vegetative growth, silking and blister period, and post blister period. Here, diverging points in time for the yield relevant processes of disposition, differentiation, and remission of ovule determine the choice of stage distinction also for other species. Experiments based on different species and cultivars are proposed to compare the results concerning quantification of thresholds and growth performance behavior. Specific consideration should be given to training effects, as stress training before reproductive stages can have positive effect on stress tolerance in further stages [WVJ⁺14].

As also introduced in sections 2.1 and 3.1, stress avoidance becomes as well evident in a displacement of biomass partitioning. Transient water deficit events are known to influence root growth (e.g. depth, density, distribution), allowing plants under field conditions to activate additional water resources and to maintain water supply despite reduced soil water content [BPV16]. Here, different soil water availabilities in terms of irrigation intervals and irrigation depth can result in differing root:shoot-ratio and leaf area [Cea16], [GSL⁺17]. Further, under field conditions different soil textures and compositions can lead to different soil desiccation speed and distributions. This can have an effect on the specific plant behavior, as e.g. very slow soil desiccation provides plants with more time to adopt than fast soil desiccation. An additional investigation of root growth behavior in combination with the observed, corresponding leaf growth can detail the proposed state machine model regarding biomass partitioning.

Finally, deficit irrigation utilizing the proposed control method requires precise irrigation and sensing techniques. The tight control of small irrigation amounts per interval also effects processes beyond plant considerations, e.g. soil salinity. Research regarding long term side effects of deficit irrigation methods should be envisaged, to quantify the trade-off between short-term and long-term water use efficiency in agricultural production.

Regarding the results on leaf temperature oscillation analysis for remotely sensed stress state determination further experiments are recommended to increase the data base and sampling rate. Maize can potentially not be the suitable plant for this specific research purpose, if the assumption of anisohydric behavior (cf. section 3.2.1) would be valid. In any case, the measurement of other crops like wheat should be envisaged.

Bibliography

- [AAC⁺99] T. Ameglio, P. Archer, M. Cohen, C. Valancogne, FA. Daudet, S. Dayau, and Cruiziat P. Significance and limits in the use of predawn leaf water potential for tree irrigation. *Plant and Soil*, 207(2):155–167, 1999.
- [AAKHS14] SH. Ahmadi, M. Agharezaee, AA. Kamgar-Haghighi, and AR. Sepaskhah. Effects of dynamic and static deficit and partial root zone drying irrigation strategies on yield, tuber sizes distribution, and water productivity of two field grown potato cultivars. *Agricultural Water Management*, 134:126–136, 2014.
- [ABB⁺09] D. Angeli, DG. Bates, E. Bullinger, PS. Chang, and DD. Vecchio. *Control Theory and Systems Biology*. MIT Press, Cambridge, Massachusetts, New York, 2nd edition, 2009.
- [ABF⁺10] W. Amelung, HP. Blume, H. Fleige, R. Horn, E. Kandeler, I. Kögel-Knabner, R. Kretschmar, K. Stahr, and BM. Wilke. *Scheffer/Schachtschabel: Lehrbuch der Bodenkunde*, volume 53. Spektrum Akademischer Verlag, Heidelberg, 16th edition, 2010.
- [ACB15] AA. Andales, JL. Chavez, and TA. Bauder. Irrigation Scheduling: The Water Balance Approach. page 6. Fort Collins, 2015.
- [AD52] TW. Anderson and DA. Darling. Asymptotic theory of certain goodness-of-fit criteria based on stochastic processes. *Ann. Math. Stat*, 23:193—212, 1952.
- [Ade04] KO. Adekalu. Adapting Crop-Yield Models to Irrigation Scheduling in Nigeria. *Food Reviews International*, 20(4):309–328, 2004.
- [AE12] Jose L. Araus and Et.al. Phenotyping maize for adaptation to drought. *Frontiers in Physiology*, 3(8):1–20, 2012.
- [AFNN11] WL. Araujo, AR. Fernie, and A. Nunes-Nesi. Control of stomatal aperture: A renaissance of the old guard. *Plant Signaling & Behavior*, 6(9):1305–1311, 2011.
- [AH00] P. Abrahamsen and S. Hansen. Daisy: An open soil-crop-atmosphere system model. *Environmental Modelling and Software*, 15(3):313–330, 2000.
- [AHMU04] VI. Adamchuk, JW. Hummel, MT. Morgan, and SK. Upadhyahya. On-the-go soil sensors for precision agriculture. *Computers and Electronics in Agriculture*, 44(1):71–91, 2004.

- [AMI⁺08] JM. Abrisqueta, J. Mounzer, O. Ivarez, S. Conejero, W. Garca-Orellana, Y. Tapia, L. Vera, I. Abrisqueta, and M.C. Ruiz-Sanchez. Root dynamics of peach trees submitted to partial rootzone drying and continuous deficit irrigation. *Agricultural Water Management*, 95(8):959–967, 2008.
- [Ape67] P. Apel. Über rhythmisch verlaufende Änderungen in der CO₂ Aufnahme von Blättern. *Bericht der deutschen Botanischen Gesellschaft*, 80:3–9, 1967.
- [APHJ11] RG. Allen, LS. Pereira, TA. Howell, and ME. Jensen. Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agricultural Water Management*, 98(6):899–920, 2011.
- [APRS98] RG. Allen, LS. Pereira, D. Raes, and M. Smith. Crop evapotranspiration: guidelines for computing crop water requirements. FAO irrigation and drainage paper 56. Technical report, Food and Agricultural Organization of the United Nations (FAO), Rome, 1998.
- [AR07] RG. Allen and CW. Robison. Evapotranspiration and Consumptive Irrigation Water Requirements for Idaho. Precipitation Deficit Table for Boise WSFO Airport. Technical Report 04, University of Idaho Research and Extension Center, Kimberly, 2007.
- [ARR⁺15] A. Attia, N. Rajan, G. Ritchie, S. Cui, A. Ibrahim, D. Hays, Q. Xue, and J. Wilborn. Yield, Quality, and Spectral Reflectance Responses of Cotton under Subsurface Drip Irrigation. *Agronomy Journal*, 107(4):1355–1364, 2015.
- [ASA15] ASA. American Society of Agronomy - Evapotranspiration Measurement and Modeling Community. (www.agronomy.org [last accessed 2015-12-10]), 2015.
- [Asc00] F. Asch. Determination of Abscisic Acid by indirect Enzyme Linked Immuno Sorbent Assay (ELISA). Technical report, The Royal Veterinary and Agricultural University, Agrohydrology & Bioclimatology, Denmark, Technical Series 1-2000, Taastrup, 2000.
- [ASRHB13] D. Al-Shrafany, MAR. Ramirez, D. Han, and M. Bray. Comparative assessment of soil moisture estimation from land surface model and satellite remote sensing based on catchment water balance. *Meteorological Applications*, 534(1), 2013.
- [AWH⁺11] MCR. Alberto, R. Wassmann, T. Hirano, A. Miyata, R. Hatano, A. Kumar, A. Padre, and M. Amante. Comparisons of energy balance

- and evapotranspiration between flooded and aerobic rice fields in the Philippines. *Agricultural Water Management*, 98(9):1417–1430, 2011.
- [Bar71] HD. Barrs. Cyclic variations in stomatal aperture, transpiration, and leaf water potential under constant environmental conditions. *Annual Review of Plant Physiology*, 22:223–236, 1971.
- [Bay08] Bayerische Landesanstalt für Landwirtschaft. LfL Information: Bewässerung im Ackerbau und in gärtnerischen Freilandkulturen. Technical report, Freising, 2008.
- [Ben12] T. Benesch. *Schlüsselkonzepte zur Statistik: Die wichtigsten Methoden, Verteilungen, Tests anschaulich erklärt*. Springer Spektrum Akademischer Verlag, Berlin Heidelberg New York, 2012.
- [BEZ⁺13] H. Bramley, W. Ehrenberger, U. Zimmermann, J. Palta, S. Rueger, and K. Siddique. Non-invasive pressure probes magnetically clamped to leaves to monitor the water status of wheat. *Plant and Soil*, 369(1-2):257–268, 2013.
- [BGE09] A. Ben-Gal and Et.al. Evaluating water stress in irrigated olives: Correlation of soil water status, tree water status, and thermal imagery. *Irrigation Science*, 27(5):367–376, 2009.
- [BGJ⁺03] N. Brisson, C. Gary, E. Justes, R. Roche, B. Mary, D. Ripoche, D. Zimmer, J. Sierra, P. Bertuzzi, P. Burger, F. Bussiere, YM. Cabidoche, P. Cellier, P. Debaeke, JP. Gaudillere, C. Henault, F. Maraux, B. Seguin, and H. Sinoquet. An overview of the crop model STICS. *European Journal of Agronomy*, 18(3-4):309–332, 2003.
- [BGJ15] BB. Buchanan, W. Gruissem, and RL. Jones. *Biochemistry & Molecular Biology of Plants*. Wiley-Blackwell, Oxford, 2nd edition, 2015.
- [BGKA⁺10] A. Ben-Gal, D. Kool, N. Agam, GE. van Halsema, U. Yermiyahu, A. Yafe, E. Presnov, R. Erel, A. Majdop, I. Zipori, E. Segal, S. Rger, U. Zimmermann, Y. Cohen, V. Alchanatis, and A. Dag. Whole-tree water balance and indicators for short-term drought stress in non-bearing 'Barnea' olives. *Agricultural Water Management*, 98(1):124–133, 2010.
- [BHM88] D. Baldocchi, BB. Hincks, and TP. Meyers. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology*, 69:1331–1340, 1988.
- [Bit10] M. Bittelli. Measuring Soil Water Potential for Water Management in Agriculture: A Review. *Sustainability*, 2(5):1226–1251, 2010.

- [BJ73] T. Brogardh and A. Johnsson. Oscillatory Transpiration and Water Uptake of Avena Plants. II Effects of Deformation of Xylem Vessels. *Physiologia Plantarum*, 28:341–345, 1973.
- [BJHP98] KJ. Boote, J. Jones, G. Hoogenboom, and N. Pickering. The CROP-GRO model for grain legumes. In P. K. Thornton, editor, *Understanding Options for Agricultural Production*, pages 99–128. Kluwer Academic Publishers, Dordrecht, The Netherlands, 1998.
- [BJK74] T. Brogardh, A. Johnsson, and R. Klockare. Oscillatory Transpiration and Water Uptake of Avena Plants V. Influences of the Water Potential of the Root Medium. *Physiologia Plantarum*, (32):258–267, 1974.
- [BJR11] B. Breckling, F. Jopp, and H. Reuter. System Analysis and Context Assessment. In *Modelling Complex Ecological Dynamics*, pages 43–54. Springer-Verlag, 1st edition, 2011.
- [BLID11] TL. Bergman, AS. Lavine, FP. Incropera, and DP. Dewitt. *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons, Ltd., 7th edition, 2011.
- [Blu96] A. Blum. Crop responses to drought and the interpretation of adaptation. *Plant Growth Regulation*, 20(2):135–148, 1996.
- [BML14] J. Blumenthal, DB. Megherbi, and R. Lussier. Unsupervised machine learning via Hidden Markov Models for accurate clustering of plant stress levels based on imaged chlorophyll fluorescence profiles & their rate of change in time. In *IEEE Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications*, pages 76–81, Lowell, 2014. CIVEMSA 2014.
- [BO07] A. Balendonck and A. Osann. Farm Level Optimal Water Management: Assistant for Irrigation under Deficit (FLOW AID). In *Proceeding Final Workshop*, pages 1–7, Wageningen, 2007.
- [Bos04] H. Bossel. *Systeme, Dynamik, Simulation: Modellbildung, Analyse und Simulation komplexer Systeme*. Books on Demand GmbH, Norderstedt, 1st edition, 2004.
- [Bou12] C. Bouchard. Genomic predictors of trainability. *Exp. Physiol.*, 3(97):347–352, 2012.
- [Bow26] IS. Bowen. The ratio of heat losses by conduction and by evaporation from any water surface. *Physics Rev.*, 27:779–787, 1926.

- [Boy82] JS. Boyer. Plant productivity and environment. *Science*, 218:443–448, 1982.
- [Boy04] JS. Boyer. Grain yields with limited water. *Journal of Experimental Botany*, 55(407):2385–2394, 2004.
- [BPH89] C. Brouwer, K. Prins, and M. Heibloem. Irrigation Scheduling. In *Irrigation Water Management, Training Manual No. 4*, page 66. UN Food and Agriculture Organization, FAO, Rome, 1989.
- [BPV16] J. Berger, J. Palta, and V. Vandez. Review: An integrated framework for crop adaptation to dry environments: Responses to transient and terminal drought. *Plant Science*, 253:58–67, 2016.
- [Bra97] E. Bray. Plant responses to water deficit. *Trends in Plant Science*, 2(2):48–54, 1997.
- [BS17] N. Beganovic and D. Söffker. Remaining lifetime modeling using State-of-Health estimation. *Mech. Syst. Sig. Process*, 92:107–123, 2017.
- [BSHC97] RW. Breidenbach, MJ. Saxton, LD. Hansen, and RS. Criddle. Heat Generation and Dissipation in Plants: Can the Alternative Oxidative Phosphorylation Pathway Serve a Thermoregulatory Role in Plant Tissues Other Than Spacialized Organs? *Plant Physiology*, 114:1137–1140, 1997.
- [BTS13] H. Bramley, N. Turner, and K. Siddique. Water Use Efficiency. In Kole C., editor, *Genomics & Breeding for Climate-Resilient Crops*, chapter 6, pages 225–268. Springer-Verlag, Berlin Heidelberg, 2 edition, 2013.
- [Buc07] E. Buckingham. Water retention in soil. In *Soil Bulletin*, volume 33. U.S. Department of Agriculture, 1907.
- [Bur13] G. Burba. *Eddy Covariance Method for Scientific, Industrial, Agricultural and Regulatory Applications: a Field Book on Measuring Ecosystem Gas Exchange and Areal Emission Rates*. LI-COR Biosciences, Lincoln, USA, 2013.
- [BWB06] N. Brisson, J. Wery, and K. Boote. Fundamental concepts of crop models illustrated by a comparative approach. In *Working with Dynamic Crop Models*, pages 257–280. Elsevier LTD, Oxford, 2nd edition, 2006.

- [CAM⁺05] Y. Cohen, V. Alchanatis, M. Meron, Y. Saranga, and J. Tsipris. Estimation of leaf water potential by thermal imagery and spatial analysis. *Journal of Experimental Botany*, 56(417):1843–1852, 2005.
- [CB82] KL. Clawson and BL. Blad. Infrared Thermometry for Scheduling irrigation of Corn. *Agronomy Journal*, 74(2):311, 1982.
- [CBE⁺05] J. Cifre, J. Bota, JM. Escalona, H. Medrano, and J. Flexas. Physiological tools for irrigation scheduling in grapevine (*Vitis vinifera* L.): An open gate to improve water-use efficiency? *Agriculture, Ecosystems and Environment*, 106(2-3 Spec. Iss.):159–170, 2005.
- [CBF⁺09] U. Conrath, GJ. Beckers, V. Flors, P. Garca-Agustn, G. Jakab, F. Mauch, MA. Newman, Poinssot B. Pieters, CM., MJ. Pozo, A. Pugin, U. Schaffrath, J. Ton, D. Wendehenne, L. Zimmerli, and B. Mauch-Mani. Priming : Getting Ready for Battle. *The American Phytopathological Society*, 19(10):1062–1071, 2009.
- [CBGB91] GJ. Collatz, JT. Ball, C. Grivet, and JA. Berry. Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer. *Agricultural and Forest Meteorology*, 54(2-4):107–136, 1991.
- [CBM⁺14] E. Chakwizira, HE. Brown, ED. Meenken, RN. Gillespie, S. Maley, MJ. George, AJ. Michel, and SJ. Dellow. Effects of timing of drought stress on grain yield of feed wheat. *Agronomy New Zealand*, 44:1–13, 2014.
- [CBP⁺14] CF. Caldeira, M. Bosio, B. Parent, L. Jeanguenin, F. Chaumont, and F. Tardieu. A Hydraulic Model Is Compatible with Rapid Changes in Leaf Elongation under Fluctuating Evaporative Demand and Soil Water Status. *Plant Physiology*, 164(4):1718–1730, 2014.
- [Cea16] Q. Chai et al. Regulated deficit irrigation for crop production under drought stress . A review. *Agronomy for Sustainable Development*, 36(3):1–21, 2016.
- [Cha91] MM. Chaves. Effects of Water Deficits on Carbon Assimilation. *Journal of Experimental Botany*, 42(1):1–16, 1991.
- [CJJ81] WJ. Conover, ME. Johnson, and MM. Johnson. Comparative Study of Tests for Homogeneity of Variances, with Applications to the Outer Continental Shelf Bidding Data. *Technom.*, 23(4):351–361, 1981.
- [Cla34] E. Clapeyron. Mémoire sur la puissance motrice de la chaleur. *Journal de l'École Polytechnique*, XIV:153–190, 1834.

- [CLL⁺09] L. Chaerle, S. Lenk, I. Leinonen, L. Jones, D. Straeten, and C. Buschmann. Multi-sensor imaging of plant stress: Towards the development of a stress-catalogue. *Biotechnology Journal*, 4(8):1152–1208, 2009.
- [CMP03] MM. Chaves, JP. Maroco, and JS. Pereira. Understanding Plant Responses to Drought - From Genes to Whole Plant. *Functional Plant Biology*, 30:239–264, 2003.
- [Coh88] J. Cohen. *Statistical Power Analysis For The Behavioral Sciences*. Lawrence Erlbaum Associates, 2nd edition, 1988.
- [CPM⁺02] MM. Chaves, JS. Pereira, J. Maroco, ML. Rodrigues, CPP. Ricardo, ML. Osoa Rio, I. Carvalho, T. Faria, and C. Pinheiro. How plants cope with water stress in the field. Photosynthesis and growth. *Annals of Botany*, 89(SPEC. ISS.):907–916, 2002.
- [CTD⁺19] LH. Comas, TJ. Trout, KC. DeJonge, H. Zhang, and SM. Gleason. Water productivity under strategic growth stage-based deficit irrigation in maize. *Agricultural Water Management*, 212:433–440, 2019.
- [Cur36] OF. Curtis. Leaf Temperatures and the Cooling of Leaves by Radiation. *Plant Physiology*, 11(2):343–364, 1936.
- [CUS⁺] CSIRO, University of Queensland, State of Queensland, AgResearch Ltd., and University of Southern Queensland. The Agricultural Production Systems Simulator (APSIM), APSIM Initiative (www.apsim.info [accessed: 25.11.2015]), 2015.
- [CVBJ14] V. Couvreur, J. Vanderborgh, L. Beff, and M. Javaux. Horizontal soil water potential heterogeneity: Simplifying approaches for crop water dynamics models. *Hydrology and Earth System Sciences*, 18(5):1723–1743, 2014.
- [CvdS00] L. Chaerle and D. van der Straeten. Imaging techniques and the early detection of plant stress. *Trends in plant science*, 5(11):495–501, 2000.
- [CZF⁺10] MM. Chaves, O. Zarrouk, R. Francisco, JM. Costa, T. Santos, AP. Regalado, ML. Rodrigues, and CM. Lopes. Grapevine under deficit irrigation: hints from physiological and molecular data. *Annals of botany*, 105(5):661–676, 2010.
- [Dal01] J. Dalton. On evaporation. *Experimental Essays*, 3:574–594, 1801.

- [Dat11] P. Datt. Latent Heat of Vaporization/Condensation. In VP. Singh, P. Singh, and UK. Haritashya, editors, *Encyclopedia of Snow, Ice and Glaciers*. Springer Netherlands, Dordrecht, 2011.
- [DDM09] SL. Davis, MD. Dukes, and GL. Miller. Landscape irrigation by evapotranspiration-based irrigation controllers under dry conditions in Southwest Florida. *Agricultural Water Management*, 96(12):1828–1836, 2009.
- [Dee08] D. Deery. *Plant water uptake at the single plant scale: experiment vs. model*. PhD thesis, 2008.
- [DFA12] Y. Ding, M. Fromm, and Z. Avramova. Multiple exposures to drought 'train' transcriptional responses in Arabidopsis. *Nature Communications*, 3:740–749, 2012.
- [DGH78] WJ. Davies, K. Gill, and G. Halliday. The Influence of Wind on the Behaviour of Stomata of Photosynthetic Stems of *Cytisus scoparius* (L.) Link. *Annals of Botany*, 42:1149–1154, 1978.
- [DHR00] D. Desclaux, TT. Huynh, and P. Roumet. Identification of Soybean Plant Characteristics That Indicate the Timing of Drought Stress. *Crop Science*, 40(3):716, 2000.
- [DKLJ10] X. Draye, Y. Kim, G. Lobet, and M. Javaux. Model-assisted integration of physiological and environmental constraints affecting the dynamic and spatial patterns of root water uptake from soils. *Journal of Experimental Botany*, 61(8):2145–2155, 2010.
- [DO05] W. Durner and D. Or. Soil Water Potential Measurement. In M.G. Anderson, editor, *Encyclopedia of Hydrological Sciences*, chapter 73, pages 1–14. John Wiley & Sons, Ltd., 2005.
- [DSCU10] G. Damour, T. Simonneau, H. Cochard, and L. Urban. An overview of models of stomatal conductance at the leaf level. *Plant, Cell and Environment*, 33(9):1419–1438, 2010.
- [dSMdS⁺05] CR. de Souza, JP. Maroco, TP. dos Santos, ML. Rodrigues, C. Lopes, JS. Pereira, and MM. Chaves. Control of stomatal aperture and carbon uptake by deficit irrigation in two grapevine cultivars. *Agriculture, Ecosystems and Environment*, 106(2-3 SPEC. ISS.):261–274, 2005.
- [DVW96] DVWK. Ermittlung der Verdunstung von Land- und Wasserflächen Vorwort. *DVWK-Merkblätter zur Wasserwirtschaft 238*, pages 1–5, 1996.

- [DWJ16] S. Daryanto, L. Wang, and PA. Jacinthe. Global Synthesis of Drought Effects on Maize and Wheat Production. *PLoS One*, 11(5), 2016.
- [DZYD11] WJ. Davies, J. Zhang, J. Yang, and IC. Dodd. Novel crop science to improve yield and resource use efficiency in water-limited agriculture. *Journal of Agricultural Science*, 149:123–131, 2011.
- [Ehl96] W. Ehlers. *Wasser in Boden und Pflanze*. Verlag Eugen Ulmer, Stuttgart, 1996.
- [ESSW09] W. Eifler, E. Schlücker, U. Spicher, and G. Will. *Küttner Kolbenmaschinen*. Vieweg+Teubner Verlag., Wiesbaden, 2009.
- [ETH+04] J. Eitzinger, M. Trnka, J. Hösch, Z. Zaludb, and M. Dubrovsky. Comparison of CERES, WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. *Ecological Modelling*, 171(3):223–246, 2004.
- [Far92] M. Farge. Wavelet Transforms and their Applications in Turbulence. *Annual Review on Fluid Mechanics*, 24:395–457, 1992.
- [FBMG08] S. Forcat, MH. Bennett, JW. Mansfield, and MR. Grant. A rapid and robust method for simultaneously measuring changes in the phytohormones ABA, JA and SA in plants following biotic and abiotic stress. *Plant Methods*, 4(1):16, 2008.
- [FDF07] PJ. Franks, PL. Drake, and R. Froend. Anisohydric but Isohydrodynamic: Seasonally Constant Plant Water Potential Gradient Explained by a Stomatal Control Mechanism Incorporating Variable Plant Hydraulic Conductance. *Plant Cell and Environment*, 30:1:19–30, 2007.
- [Fer14] J. E. Fernández. Plant-based sensing to monitor water stress: Applicability to commercial orchards. *Agricultural Water Management*, 142:99–109, 2014.
- [Fis60] RA. Fisher. *The Design of Experiments*. Oliver&Boyd, Edinburgh, UK, 7th edition, 1960.
- [FP13] DK. Fisher and HC. Pringle III. Evaluation of alternative methods for estimating reference evapotranspiration. *Agricultural Sciences*, 04(08):51–60, 2013.
- [FS07] E. Fereres and M. Soriano. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, 58(2):147–159, 2007.

- [FSM18] M. Flörke, C. Schneider, and R.I. McDonald. Water competition between cities and agriculture driven by climate change and urban growth. In *Nat. Sustain.*, volume 1, pages 51–58, 2018.
- [Fuc90] M. Fuchs. Theoretical and Applied Climatology Infrared Measurement of Canopy Temperature and Detection of Plant Water Stress. *Theor. Appl. Climatol.*, 261:253–261, 1990.
- [GA11] W.H. Green and G.A. Ampt. Studies of soil physics, part 1, the flow of air and water through soils. *Journal of Agricultural Science*, 4:1–24, 1911.
- [Gal89] F. Galton. Co-relation and their measurement. In *Proc. R. Soc. Lond.*, volume 45, pages 135–145, 1889.
- [Gal94] F. Galton. *Natural Inheritance*. Macmillan and Company, New York, 5th edition, 1894.
- [Gat68] D.M. Gates. Transpiration and Leaf Temperature. *Annual Review on Plant Physiology*, 19:211–238, 1968.
- [GDLO18] S.J. Greenland, J. Dalrymple, E. Levin, and B. OMahony. Improving agricultural water sustainability: Strategies for effective farm water management and encouraging the uptake of drip irrigation. In D. Crowther, S. Seiii, and A. Moyeen, editors, *The Goals of Sustainable Development: Responsibility and Governance*, pages 111–123. Springer Singapore, 2018.
- [GDNM⁺09] M.P. Gonzalez-Dugo, C.M.U. Neale, L. Mateos, W.P. Kustas, J.H. Prueger, M.C. Anderson, and F. Li. A comparison of operational remote sensing-based models for estimating crop evapotranspiration. *Agricultural and Forest Meteorology*, 149(11):1843–1853, 2009.
- [GDZTF14] V. Gonzalez-Dugo, P.J. Zarco-Tejada, and E. Fereres. Applicability and limitations of using the crop water stress index as an indicator of water deficits in citrus orchards. *Agricultural and Forest Meteorology*, 198-199:94–104, 2014.
- [GE01] J.W. Gowing and C.J. Ejieji. Real-time scheduling of supplemental irrigation for potatoes using a decision model and short-term weather forecasts. *Agricultural Water Management*, 47(2):137–153, 2001.
- [GFP⁺15] S. Gebler, H.H.J. Franssen, T. Pütz, H. Post, M. Schmidt, and H. Vereecken. Actual evapotranspiration and precipitation measured by lysimeters: a comparison with eddy covariance and tipping bucket. *Hydrology and Earth System Sciences*, 19(5):2145–2161, 2015.

- [GGH⁺07] LC. Guerra, A. Garcia, JE. Hook, KA. Harrison, DL. Thomas, DE. Stooksbury, and G. Hoogenboom. Irrigation water use estimates based on crop simulation models and kriging. *Agricultural Water Management*, 89(3):199–207, 2007.
- [GIK⁺13] L. Genc, M. Inalpulat, U. Kizil, M. Mirik, SE. Smith, and M. Mendes. Determination of water stress with spectral reflectance on sweet corn (*Zea mays* L.) using classification tree (CT) analysis. *Zemdirbyste-Agriculture*, 100(1):81–90, 2013.
- [GJKA89] RF. Grant, BS. Jackson, JR. Kiniry, and GF. Arkin. Comparison of deficit irrigation management strategies on root, plant growth and biomass productivity of silage maize. *Agronomy Journal*, 81:61–65, 1989.
- [GKC06] SR. Green, MB. Kirkham, and BE. Clothier. Root uptake and transpiration: From measurements and models to sustainable irrigation. *Agricultural Water Management*, 86(1-2):165–176, 2006.
- [G11] B. Glück. *Zustands- und Stoffwerte: Wasser, Dampf, Luft*. Verlag für Bauwesen GmbH, Berlin, 2nd edition, 1991.
- [GMdC⁺06] J. Girona, M. Mata, J. del Campo, A. Arbones, E. Bartra, and J. Marsal. The use of midday leaf water potential for scheduling deficit irrigation in vineyards. *Irrigation Science*, 24:115–127, 2006.
- [GML07] C. Garcia-Mata and L. Lamattina. Abscisic acid (ABA) inhibits light-induced stomatal opening through calcium- and nitric oxide-mediated signaling pathways. *Nitric Oxide*, 17:143–151, 2007.
- [GR09] S. Geerts and D. Raes. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, 96(9):1275–1284, 2009.
- [GRG10] S. Geerts, D. Raes, and M. Garcia. Using AquaCrop to derive deficit irrigation schedules. *Agricultural Water Management*, 98(1):213–216, 2010.
- [GSL⁺17] M. Gheysari, Sadeghi SH., HW. Loescher, S. Amiri, MJ. Zareian, MM. Majidi, P. Asgarini, and JO. Payero. Comparison of deficit irrigation management strategies on root, plant growth and biomass productivity of silage maize. *Agricultural Water Management*, 182:126–138, 2017.
- [GSS⁺97] U. Gisi, R. Schenker, R. Schulin, FX. Stadelmann, and H. Sticher. *Bodenoekologie*, volume 2. Thieme Verlag, Stuttgart, New York, 1997.

- [GVB⁺16] M. Gagliano, VV. Vyazovskiy, AA. Borbly, M. Grimonprez, and M. Depczynski. Learning by Association in Plants. *Scientific Reports*, 6(December):1–9, 2016.
- [GVFM⁺09] M. Garcia-Vila, E. Fereres, L. Mateosa, F. Orgaza, and P. Steduto. Deficit Irrigation Optimization of Cotton with Aquacrop. *Agronomy Journal*, 101(3):477–487, 2009.
- [GY17] B. Guo and Y. Yuan. A comparative review of methods for comparing means using partially paired data. *Stat. Methods Med. Res.*, 26(3):1323–1340, 2017.
- [Han02] S. Hansen. Daisy, a flexible soil-plant-atmosphere system model. Technical report, The Royal Veterinary- and Agricultural University, Copenhagen, 2002.
- [HBV12] NI. Huth, KL. Bristow, and K. Verburg. Swim3: Model Use, Calibration, and Validation. *Transactions of the ASABE*, 55(4):1303–1313, 2012.
- [HCB13] J. He, H. Caia, and J. Bai. Irrigation scheduling based on CERES-Wheat model for spring wheat production in the Minqin Oasis in Northwest China. *Agricultural Water Management*, 128:19–31, 2013.
- [HCZ⁺04] JC. Hu, WX. Cao, JB. Zhang, D. Jiang, and J. Feng. Quantifying responses of winter Wheat physiological processes to soil water stress for use in growth simulation modeling. *Pedosphere*, 14(4):509–518, 2004.
- [HDCL12] MA. Hardie, RB. Doyle, WE. Cotching, and S. Lisson. Subsurface Lateral Flow in Texture-Contrast (Duplex) Soils and Catchments with Shallow Bedrock. *Applied and Environmental Soil Science*, pages 1–10, 2012.
- [HHd⁺14] DP. Holzworth, NI. Huth, PG. deVoil, EJ. Zurcher, NI. Herrmann, G. McLean, K. Chenu, EJ. Oosterom, V. Snow, C. Murphy, AD. Moore, H. Brown, JPM. Whish, S. Verrall, J. Fainges, LW. Bell, AS. Peake, PL. Poulton, Z. Hochman, and PJ. Thorburn et al. APSIM - Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling and Software*, 62:327–350, 2014.
- [HJ98] H. Høgh-Jensen. Systems Theory as a Scientific Approach towards Organic Farming. *Biological Agriculture & Horticulture: An International Journal for Sustainable Production Systems*, 16(1):37–52, 1998.

- [Hoo94] JE. Hook. Using crop models to plan water withdrawals for irrigation in drought years. *Agricultural Systems*, 45(3):271–289, 1994.
- [How96] TA. Howell. Irrigation scheduling research and its impact on water use. In *Evapotranspiration and Irrigation Scheduling*, pages 21–33. American Society of Agricultural Engineers, San Antonio, 1996.
- [How16] DC. Howell. *Fundamental statistics for the behavioral sciences*. Cengage learning, Nelson education Ltd., 9th edition, 2016.
- [Hsi73] TC. Hsiao. Plant Responses To Water Stress. *Ann. Rev. Plant Physiol.*, 24:519–570, 1973.
- [HSV11] KE. Hubbard, RS. Siegel, and G. Valerio. Abscisic acid and CO₂ signalling via calcium sensitivity priming in guard cells, new CDPK mutant phenotypes and a method for improved resolution of stomatal stimulus-response analysis. *Annals of Botany*, 109:5–17, 2011.
- [HW08] NE. Huang and Z. Wu. A Review in Hilbert-Huang Transform: Method and its Applications to Geophysical Studies. *Reviews of Geophysics*, 46(RG2006), 2008.
- [HW15] KE. Hubbard and AAR. Webb. Circadian Rhythms in Stomata: Physiological and Molecular Aspects. In S. Mancuso and S. Shabala, editors, *Rhythm in Plants: Dynamic Responses in a Dynamic Environment.*, pages 231–255. Springer International Publishing, Switzerland, 2nd edition, 2015.
- [HWL16] NE. Huang, MLC. Wu, and SR. Long. A confidence limit for the empirical mode decomposition and Hilbert spectral analysis. *Proc. R. Soc. Lond., A* 459:2317—2345, 2016.
- [IJR78] SB. Idso, RD. Jackson, and RJ. Reginato. Extending the "Degree Day" Concept of Plant Phenological Development to Include Water Stress Effects. *Ecology*, 59(3):431–433, 1978.
- [Jac82] RD. Jackson. Canopy Temperature and Crop Water Stress. In D. Hillel, editor, *Advances in Irrigation*, volume 1, pages 43–86. Academic Press, Inc., New York, 1982.
- [Jak77] NN. Jakovlev. Sportbiochemie. *Sportmedizinische Schriftenreihe der Deutschen Hochschule für Körperkultur*, 1977.
- [JBP⁺10] CR. Jensen, A. Battilani, F. Plauborg, G. Psarras, K. Chartzoulakis, F. Janowiak, R. Stikic, Z. Jovanovic, G. Lig, x. Qi, F. Liu, SE. Jacobsen, and MN. Andersen. Deficit irrigation based on drought

- tolerance and root signalling in potatoes and tomatoes. *Agricultural Water Management*, 98(3):403–413, 2010.
- [JGG⁺11] M. Janott, S. Gayler, A. Gessler, M. Javaux, C. Klier, and E. Priesack. A one-dimensional model of water flow in soil-plant systems based on plant architecture. *Plant and Soil*, 341(1-2):233–256, 2011.
- [JIRPJ81] RD. Jackson, SB. Idso, RJ. Reginato, and PJ. Pinter Jr. Canopy temperature as a crop water stress indicator. *Water Resources Research*, 17(4):1133–1138, 1981.
- [JKC88] RD. Jackson, WP. Kustas, and BJ. Choudhury. A reexamination of the crop water stress index. *Irrig. Sci.*, 9:309–317, 1988.
- [JKRO16] E. Janka, O. Körner, E. Rosenqvist, and CO. Ottosen. A coupled model of leaf photosynthesis, stomatal conductance, and leaf energy balance for chrysanthemum (*Dendranthema grandiflora*). *Computers and Electronics in Agriculture*, 123:264–274, 2016.
- [Joh15] A. Johnsson. Oscillations in Plant Transpiration. In S. Mancuso and P. Shabala, editors, *Rhythm in plants: Dynamic Responses in a Dynamic Environment.*, pages 157–188. Springer International Publishing, Switzerland, 2nd edition, 2015.
- [Jon99] HG. Jones. Use of infrared thermometry for estimation of stomatal conductance in irrigation scheduling. *Agricultural and Forest Meteorology*, 95:139–149, 1999.
- [Jon04] HG. Jones. Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany*, 55(407):2427–2436, 2004.
- [Jon07] HG. Jones. Monitoring plant and soil water status: Established and novel methods revisited and their relevance to studies of drought tolerance. *Journal of Experimental Botany*, 58(2):119–130, 2007.
- [JS08] HG. Jones and P. Schofield. Thermal and Other Remote Sensing of Plant Stress. *Gen. Appl. Plant Physiology*, 34 (Spec.(1-2):19–32, 2008.
- [JS14] HG. Jones and X. Sirault. Scaling of Thermal Images at Different Spatial Resolution: The Mixed Pixel Problem. *Agronomy*, 4(3):380–396, 2014.
- [JT98] HG. Jones and F. Tardieu. Modelling water relations of horticultural crops: a review. *Scientia Horticulturae*, 74(1-2):21–46, 1998.

- [Kad06] RH. Kadlec. Water temperature and evapotranspiration in surface flow wetlands in hot arid climate. *Ecological Engineering*, 26(4):328–340, 2006.
- [KCB13] G. Kitić and V. Crnojević-Bengin. A sensor for the measurement of the moisture of undisturbed soil samples. *Sensors (Basel, Switzerland)*, 13(2):1692–705, 2013.
- [KCH⁺03] BA. Keating, PS. Carberry, GL. Hammer, ME. Probert, MJ. Robertson, D. Holzworth, NI. Huth, JNG. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, JP. Dimesad, M. Silburn, E. Wang, S. Brown, KL. Bristow, and CJ. Smith. An overview of APSIM , a model designed for farming systems simulation. *European Journal of Agronomy*, 18:267–288, 2003.
- [KFS17] S. Khanal, J. Fulton, and S. Shearer. An overview of current and potential applications of thermal remote sensing in precision agriculture. *Comp. Electr. Agr.*, 139:22–32, 2017.
- [KH31] H. Kautsky and A. Hirsch. Neue Versuche zur Kohlensäureassimilation. *Naturwissenschaften*, 19(48):964, 1931.
- [KHMW07] KC. Kersebaum, JM. Hecker, W. Mirschel, and M. Wegehenkel. Modelling water and nutrient dynamics in soil-crop systems. In *Modelling water and nutrient dynamics in soil-crop systems*, page 272, Müncheberg, 2007.
- [KK12] KD. Kammeyer and K. Kroschel. *Digitale Signalverarbeitung*. Vieweg+Teubner Verlag., Wiesbaden, 8th edition, 2012.
- [KMD⁺16] I. Kisekka, KW. Migliaccio, MD. Dukes, B. Schaffer, and JH. Crane. Evapotranspiration-based irrigation scheduling for agriculture. IFAS Extension, page 5. Gainesville, 2016.
- [KP09] J. Ko and G. Piccinni. Corn yield responses under crop evapotranspiration-based irrigation management. *Agricultural Water Management*, 96(5):799–808, 2009.
- [KPKS12] S. Kloss, R. Pushpalatha, KJ. Kamoyo, and N. Schütze. Evaluation of Crop Models for Simulating and Optimizing Deficit Irrigation Systems in Arid and Semi-arid Countries Under Climate Variability. *Water Resources Management*, 26(4):997–1014, 2012.
- [KS00] C. Kirda and P. Steduto. Soil water balance approach in crop water requirement studies in. In *Soil water balance and transport processes: Review of theory and field applications*, volume 46, pages 181–199. CIHEAM, Cahiers Options Méditerranéennes, 2000.

- [KS17] F. Kögler and D. Söffker. Water (stress) models and deficit irrigation: System-theoretical description and causality mapping. *Ecologic Modeling*, 363:135–156, 2017.
- [KS19a] F. Kögler and D. Söffker. Explorative Frequency Analysis of Leaf Temperature Behavior of Corn (zea mays) at Water Deficit. *Plants*, submitted, 2019.
- [KS19b] F. Kögler and D. Söffker. Sport for plants as a means for growth control: Water-based open-loop control of plant growth. In preparation, 2019.
- [KSJ14] R. Kumar, V. Shankar, and M. Jat. Evaluation of root water uptake models a review. *ISH Journal of Hydraulic Engineering*, (5):1–10, 2014.
- [Kut95] U. Kutschera. Wasserhaushalt der Pflanzenzelle: Diffusion, Osmose, Wasserpotential. In *Kurzes Lehrbuch der Pflanzenphysiologie*, chapter 4, page 60. Quelle und Meyer, Wiesbaden, 1995.
- [Lar87] W. Larcher. Stress bei Pflanzen. *Naturwissenschaften*, 74:158–167, 1987.
- [Lar01] W. Larcher. *Ökophysiologie der Pflanzen: Leben, Leistung und Stressbewältigung der Pflanzen in ihrer Umwelt*. Verlag Eugen Ulmer, Stuttgart, 6th edition, 2001.
- [LB17] J. Lämke and I. Bäurle. Epigenetic and chromatin-based mechanisms in environmental stress adaptation and stress memory in plants. *Genome Biology*, 18:124:1–11, 2017.
- [LdJB01] KY. Li, R. de Jong, and JB. Boisvert. An exponential root-water-uptake model with water stress compensation. *Journal of Hydrology*, 252(1-4):189–204, 2001.
- [Lev60] I. Levene. Robust tests for equality of variances. In I. Olkin and H. Hotelling et al., editors, *Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling*, pages 278–292. Stanford University Press, 1960.
- [Lev80] J. Levitt. Adaptation of Plants to Water and High Temperature Stress: Summary and Synthesis. In P. J. Turner, N. C., Kramer, editor, *Adaptation of Plants to Water and High Temperature Stress*, pages 347–456, New York, 1980. John wiley & Sons.

- [LGT⁺06] I. Leinonen, OM. Grant, CPP. Tagliavia, MM. Chaves, and HG. Jones. Estimating stomatal conductance with thermal imagery. *Plant, Cell and Environment*, 29(8):1508–1518, 2006.
- [Lic96] HK. Lichtenthaler. Vegetation Stress : an Introduction to the Stress Concept in Plants. *Journal of Plant Physiology*, 148(1-2):4–14, 1996.
- [LIS⁺16] R. Linker, I. Ioslovich, G. Sylaios, F. Plauborg, and A. Battilani. Optimal model-based deficit irrigation scheduling using AquaCrop: A simulation study with cotton, potato and tomato. *Agricultural Water Management*, 163:236–243, 2016.
- [LL16] X. Li and F. Liu. Drought Stress Memory and Drought Stress Tolerance in Plants : Biochemical and Molecular Basis. In M.A. et al. Hossain, editor, *Drought Stress Tolerance in Plants*, volume 1, chapter 2, pages 17–45. Basel, Switzerland, 1 edition, 2016.
- [LMM⁺14] C. Lozoya, C. Mendoza, L. Mejia, J. Quintana, G. Mendoza, M. Bustillos, O. Arras, and L. Solis. Model Predictive Control for Closed-Loop Irrigation. In *19th IFAC World Congress*, number 1, pages 4429–4434, 2014.
- [Lös01] R. Lösch. *Wasserhaushalt der Pflanzen*. Quelle&Meyer Verlag GmbH&Co, Wiebelsheim, 1st edition, 2001.
- [LSZ⁺08] F. Liu, R. Song, X. Zhang, A. Shahnazari, Andersen MN., F. Plauborg, SE. Jacobsen, and CR. Jensen. Measurement and modelling of ABA signalling in potato (*Solanum tuberosum* L.) during partial root-zone drying. *Environmental and Experimental Botany*, 63(1-3):385–391, 2008.
- [LTM⁺17] B. Laleh, RS. Thomas, Z. Maciej, S. Francesca, H. William, EC. Thomas, and WR. Thomas. Assessing water-related plant traits to explain slow-wilting in soybean PI 471938. *Journal of Crop Improvement*, 31(3):400–417, 2017.
- [Lun03] J. Lunze. *Automatisierungstechnik*. De Gruyter Oldenbourg Verlag, München, Wien, 2003.
- [Lun16] E. Luna. Using green vaccination to brighten the agronomic future. *Outl. Pest Managem.*, 27(3):136–140, 2016.
- [LWE⁺17] JR. Lopez, JM. Winter, J. Elliott, AC. Ruane, C. Porter, and G. Hoogenboom. Integrating growth stage deficit irrigation into a process based crop model. *Agricultural and Forest Meteorology*, 243:84–92, 2017.

- [LZH14] L. Li, Q. Zhang, and D. Huand. A Review of Imaging Techniques for Plant Phenotyping. *Sensors*, 14:20078–20111, 2014.
- [MAC⁺07] M. Möller, V. Alchanatis, Y. Cohen, M. Meron, J. Tsipris, A. Naor, V. Ostrovsky, M. Sprintsin, and S. Cohen. Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. *Journal of Experimental Botany*, 58(4):827–838, 2007.
- [Mai19] Maisfakten. ”Verbraucht” Mais viel Wasser? Deutsches Maiskomitee e.V. *www.maisfakten.de* [last accessed 2019-01-25], 2019.
- [Mas02] K. Mastel. Berechnung und Bewässerung landwirtschaftlicher und gärtnerischer Kulturen. Merkblätter für die umweltgerechte Landwirtschaft, pages 1–12. Rheinstetten, 2002.
- [MBB⁺18] A. Matese, R. Baraldi, A. Berton, C. Cesaraccio, S. Di Gennaro, P. Duce, O. Facini, M. Mameli, A. Piga, and A. Zaldei. Estimation of Water Stress in Grapevines Using Proximal and Remote Sensing Methods. *Remote Sensing*, 10(114):1–16, 2018.
- [McM08] GS. McMaster. Simulating Crop Phenological Responses to Water Deficits. In Y. Qiang L.R. Ahuja, V.R. Reddy, S.A. Saseendran, editor, *Response of Crops to limited Water: Understanding and Modeling Water Stress Effects on Plant Growth Processes*, pages 277–300. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, 2008.
- [MHZC17] Z. Miao, Z. Han, T. Zhang, and Ma C. Chen, S. and. A systems approach to a spatio-temporal understanding of the drought stress response in maize. *Scientific Reports*, 7:6590, 2017.
- [Min15] Ministry of Agriculture of British Columbia. Soil water storage capacity and available soil moisture. *Water Conservation Factsheet 619.000-1*, 1(619):2–5, 2015.
- [MJR⁺78] JP. Millard, RD. Jackson, RJ. Reginato, SB. Idso, and RC. Goettelman. Crop Water-Stress Assessment Using Airborne Thermal Scanner. *Photogrammetric Engineering and Remote Sensing*, 44:77–85, 1978.
- [MJS⁺10] R. Munns, RA James, XR. Sirault, RT. Furbank, and HG. Jones. New phenotyping methods for screening wheat and barley for beneficial responses to water deficit. *Journal of Experimental Botany*, 61(13):3499–3507, 2010.

- [MMFH⁺16] A. Martinez-Medina, V. Flors, M. Heil, B. Mauch-Mani, CMJ. Pieterse, MJ. Pozo, J. Ton, NM. van Dam, and U. Conrath. Recognizing Plant Defense Priming. *Trends in Plant Science*, 21(10):818–822, 2016.
- [Mol93] R. Mollier. *Das Wärmediagramm - Entropie-Temperatur-Diagramm*. Berlin, 1st edition, 1893.
- [Möl03] D. Möller. *Luft*. Water de Gruyter, Berlin, New York, 1st edition, 2003.
- [Mon65] JL. Monteith. Evaporation and environment. In *Symposia of the Society for Experimental Biology*, pages 205–224, 1965.
- [Mon81] JL. Monteith. Evaporation and surface temperature. *Quart. J. R. Met. Soc.*, 107:1–27, 1981.
- [MPCA89] SM. Moran, PJ. Pinter Jr., BE. Clothier, and SG. Allen. Effect of water stress on the canopy architecture and spectral indices of irrigated alfalfa. *Remote Sensing of Environment*, 29(3):251–261, 1989.
- [MPD⁺11] CD. Messina, D. Podlich, Z. Dong, M. Samples, and M. Cooper. Yield-trait performance landscapes: from theory to application in breeding maize for drought tolerance. *Journal of Experimental Botany*, 62:855–868, 2011.
- [MR11] S. Mayr and S. Rosner. Cavitation in dehydrating xylem of *Picea abies*: energy properties of ultrasonic emissions reflect tracheid dimensions. *Tree physiology*, 31(1):59–67, 2011.
- [MS12] WH. Maes and K. Steppe. Estimating evapotranspiration and drought stress with ground-based thermal remote sensing in agriculture: a review. *Journal of Experimental Botany*, 63(2):4671–4712, 2012.
- [MSAT14] KM. Meyer, LL. Soldaat, H. Auge, and HH. Thulke. Adaptive and Selective Seed Abortion Reveals Complex Conditional Decision Making in Plants. *The American Naturalist*, 183(3):376–383, 2014.
- [MSFB06] RA. Marengo, K. Siebke, GD. Farquhar, and MC. Ball. Hydraulically based stomatal oscillations and stomatal patchiness in *Gossypium hirsutum*. *Functional Plant Biology*, 33:1103–1113, 2006.
- [MU88] JR. Mahan and DR. Upchurch. Maintenance of Constant Leaf Temperature by plants - I. Hypothesis Limited Homeothermy. *Environmental and Experimental Botany*, 28(4):351–357, 1988.

- [MV18] Z. Malek and PH. Verburg. Adaptation of land management in the Mediterranean under scenarios of irrigation water use and availability. *Mitig. Adapt. Strateg. Glob. Change*, 23:821—837, 2018.
- [MVCMT15] L. McAusland, SRM. Vialet-Chabrand, JSA. Matthews, and Lawson T. Spatial and Temporal Responses in Stomatal Behaviour, Photosynthesis and Implications for Water-Use Efficiency. In S. Mancuso and S. Shabala, editors, *Rhythm in Plants: Dynamic Responses in a Dynamic Environment.*, pages 97–119. Springer International Publishing, Switzerland, 2nd edition, 2015.
- [MW47] HB. Mann and DR. Whitney. On a test of whether one of two random variables is stochastically larger than the other. *Ann. Math. Statist.*, 18(1):50–60, 1947.
- [MW97] GS. McMaster and WW. Wilhem. Growing degree days: one equation, two interpretations. *Agricultural and Forest Meteorology*, 87:291–300, 1997.
- [MYH17] MO. Meade, D. Young, and O. Hanna. Severity of Hypoxemia and Effect of High Frequency Oscillatory Ventilation in ARDS. *American Journal of Respiratory and Critical Care Medicine*, 2:doi:10.1164/rccm.201609–1938SC., 2017.
- [Nac98] M. Nachabe. Refining the Definition of Field Capacity in the Literature. *Journal of Irrigation and Drainage Engineering*, 124(4):230–232, 1998.
- [Pas82] JB. Passioura. Water in the Soil-Plant-Atmosphere Continuum. *Physiological Plant Ecology II*, 12:5–33, 1982.
- [Pen48] HL. Penman. Natural Evaporation from Open Water, Bare Soil and Grass. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, volume 193, pages 120–145, London, 1948. The Royal Society.
- [PF98] J. Penuelas and I. Filella. Visible and near-infrared reflectance techniques for diagnosing plant physiological status. *Trends in Plant Science*, 3(4):151–156, 1998.
- [PFB+93] J. Penuelas, I. Fillela, C. Biel, L. Serano, and R. Save. The reflectance at the 950-970nm region as an indicator of plant water status. *International Journal of Remote Sensing*, 14(10):1887–1905, 1993.
- [PFJ03a] G. Prytz, CM. Futsaether, and A. Johnsson. Self-sustained oscillation in plant water regulation: Induction of bifurcations and anomalous rhythmicity. *New Phytologist*, 158:258–267, 2003.

- [PFJ03b] G. Prytz, CM. Futsaether, and A. Johnsson. Thermography studies of the spatial and temporal variability in stomatal conductance of *Avena* leaves during stable and oscillatory transpiration. *New Phytologist*, 158:249–258, 2003.
- [PHB10] R. Pieruschka, G. Huber, and JA. Berry. Control of transpiration by radiation. In *Proceedings of the National Academy of Science of the United States of America* 107(30), pages 13372–13377, 2010.
- [PJ14] A. Prashar and HJ. Jones. Infra-Red Thermography as a High-Throughput Tool for Field Phenotyping. *Agronomy*, 4(3):397–417, 2014.
- [PKM09] PJ. Paschold, J. Kleber, and N. Mayer. Bewässerungssteuerung bei Gemüse im Freiland. *Landbauforschung*, Sonderheft:43–48, 2009.
- [PP11] Z. Popova and LS. Pereira. Modelling for maize irrigation scheduling using long term experimental data from Plovdiv region, Bulgaria. *Agricultural Water Management*, 98(4):675–683, 2011.
- [PT14] B. Parent and F. Tardieu. Can current crop models be used in the phenotyping era for predicting the genetic variability of yield of plants subjected to drought or high temperature? *Journal of experimental botany*, 65(21):6179–6189, 2014.
- [Ras65] K. Raschke. Die Stomata als Glieder eines schwingungsfähigen CO₂-Regelsystems: Experimenteller Nachweis an *Zea mays* L. *Zeitschrift für Naturforschung*, 20 b:1261–1270, 1965.
- [Ras70] K. Raschke. Stomatal Responses to Pressure Changes and Interruptions in the Water Supply of Detached Leaves of *Zea mays* L. *Plant Physiology*, 45:415–423, 1970.
- [RBF⁺08] M. Renger, K. Bohne, M. Facklam, T. Harrach, W. Riek, W. Schäfer, G. Wessolek, and S. Zacharias. Kennwerte des Bodengefüges zur Schätzung bodenphysikalischer Kennwerte. Technical report, DBG-Arbeitsgruppe "Kennwerte des Bodengefüges", Berlin, 2008.
- [RBGRA14] F. Rodriguez, M. Berenguel, JL. Guzman, and A. Ramirez-Arias. *Modeling and Control of Greenhouse Crop Growth*. Springer International Publishing, Switzerland, 1st edition, 2014.
- [RCB07] G. Rossi, Castiglione.L., and B. Bonaccorso. Guidelines for Planning and Implementing Drought Mitigation Measures. In *Methods and Tools for Drought Analysis and Management*, page 149ff. Springer Verlag, 2007.

- [Ric31] LA. Richards. Capillary Conduction of Liquids Through Porous Mediums. *Journal of Applied Physics*, 1:318, 1931.
- [Rit85] JT. Ritchie. A User-Orientated Model of the Soil Water Balance in Wheat. *Wheat Growth and Modelling*, 86:293–305, 1985.
- [Rit98] JT. Ritchie. Soil water balance and plant water stress. In *Understanding Options for Agricultural Production*, pages 41–54. 1998.
- [RIW⁺19] DR. Rudnick, S. Irmak, C. West, JL. Chvez, I. Kisekka, TH. Marek, JP. Schneekloth, DM. McCallister, V. Sharma, K. Djaman, J. Aguilar, ME. Schipanski, DH. Rogers, and A. Schlegel. Deficit Irrigation Management of Maize in the High Plains Aquifer Region: A Review. *Journal of the American Water Resources Association*, 1:1–18, 2019.
- [Rog15] D. Rogers. Irrigation Scheduling Based on Soil Moisture Sensors and Evapotranspiration. Technical Report 5, Kansas Agricultural Experiment Station, Kansas, 2015.
- [RPL⁺17] A. Ruggiero, P. Punzo, S. Landi, A. Costa, MA. van Oosten, and S. Grillo. Improving plant water use efficiency through molecular genetics. *Horticulturae*, 3(31):1–21, 2017.
- [RSHF12] D. Raes, P. Staduto, TC. Hsiao, and E. Fereres. AquaCrop (Version 4.0) Reference Manual. page 130. Rome, 2012.
- [RUDB98] JT. Ritchie, Singh U., Godwin DC., and WT. Bowen. Cereal growth, development and yield. *Understanding Options for Agricultural Production*, 7:79–98, 1998.
- [RYS⁺00] CA. Reynolds, M. Yitayew, DC. Slack, CF. Hutchinson, A Huete, and MS. Petersen. Estimating crop yields and production by integrating the FAO Crop Specific Water Balance model with real-time satellite data and ground-based ancillary data. *International Journal of Remote Sensing*, 21(18):3487–3508, 2000.
- [SBMH02] ED. Schulze, E. Beck, and K. Müller-Hohenstein. *Pflanzenökologie*. Spektrum Verlag/Elsevier, Heidelberg, 2002.
- [SC15] A. Subedi and JL. Chávez. Crop Evapotranspiration (ET) Estimation Models: A Review and Discussion of the Applicability and Limitations of ET Methods. *Journal of Agricultural Science*, 7(6):50, 2015.
- [Sch86] ED. Schulze. Carbon Dioxide and Water Vapor Exchange in Response to Drought in the Atmosphere and in the Soil. *Ann. Rev. Plant Physiol.*, 37:247–274, 1986.

- [SDMMH⁺17] SC. Steele-Dunne, H. McNairn, A. Monsivais-Huertero, J. Judge, P. Liu, and K. Papathanassiou. Radar Remote Sensing of Agricultural Canopies. In *IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sen*, volume 10, 2017.
- [SDO⁺13] SK. Saleem, DK. Delgoda, SK. Ooi, KB. Dassanayake, L. Liu, MN. Halgamuge, and H. Malano. Model Predictive Control for Real-Time Irrigation Scheduling. *Agricontrol*, 4(Part1):299–304, 2013.
- [SFS98] CC. Shock, EBG. Feibert, and LD. Saunders. Onion Yield and Quality Affected by Soil Water Potential as Irrigation Threshold. *HortScience*, 33(7):1188–1191, 1998.
- [SG67] PJ. Salter and JE. Goode. Crop responses to water at different stages of growth. Technical report, Commonwealth Agricultural Bureaux, Farnham Royal, Buckinghamshire, UK, 1967.
- [SGB17] MA. Sarzynski, S. Ghosh, and C. Bouchard. Genomic and transcriptomic predictors of response levels to endurance exercise training. *J. Physiol.*, 9(March 2016):2931–2939, 2017.
- [Sha06] S. Shabala. Oscillations in Plants. In F. Baluska, S. Mancuso, and D. Volkmann, editors, *Communication in Plants, Neuronal Aspects of Plant Life.*, pages 261–275. Springer-Verlag, Berlin, 2006.
- [SHFR12] P. Steduto, T. Hsiao, E. Fereres, and D. Raes. Crop yield response to water - Irrigation and Drainage Paper 66. Technical report, Rome, 2012.
- [SHK11] G. Schnabel, HD. Harre, and J. Krug. *Trainingswissenschaft*. Sportverlag, Berlin, 2011.
- [Shu08] J. Shuttleworth. Evapotranspiration Measurement Methods. *South-West Hydrology*, (2):22–23, 2008.
- [SJ05] DM. Sumner and JM. Jacobs. Utility of Penman-Monteith, Priestley-Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. *Journal of Hydrology*, 308(1-4):81–104, 2005.
- [SOZ13] SJ. Schymanski, D. Or, and M. Zwieniecki. Stomatal Control and Leaf Thermal and Hydraulic Capacitances under Rapid Environmental Fluctuations. *PLoS ONE*, 8(1):e54231. doi:10.1371/journal.pone.0054231., 2013.
- [Spe10] S. Spearman. Correlation calculated from faulty data. *Brit. Psychol. Soc*, 3(3):271–295, 1910.

- [SR86] KE. Saxton and WJ. Rawls. Estimating Generalized Soil-water Characteristics from Texture. *American Journal of Soil Science Society*, 50:1031–1036, 1986.
- [SRH⁺09] P. Steduto, D. Raes, T. Hsiao, E. Fereres, L. Heng, G. Izzi, and J. Hoogeveen. AquaCrop: a new model for crop prediction under water deficit conditions. *FAO, Rome*, 33(80):285–292, 2009.
- [SRK⁺15] A. Stadler, S. Rudolph, M. Kupisch, M. Langensiepen, J. van der Kruk, and F. Ewert. Quantifying the effects of soil variability on crop growth using apparent soil electrical conductivity measurements. *European Journal of Agronomy*, 64:8–20, 2015.
- [SS09] B. Soundharajan and KP. Sudheer. Deficit irrigation management for rice using crop growth simulation model in an optimization framework. *Paddy Water Environment*, 7(2):135–149, 2009.
- [SSB⁺14] MVK. Sivakumar, R. Stefanski, M. Bazza, S. Zelaya, D. Wilhite, and Magalhaes AR. High Level Meeting on National Drought Policy: Summary and Major Outcomes. *Weather and Climate Extremes*, 3:126–132, 2014.
- [Sto07] RG. Stockwell. A basis for efficient representation of the S-transform. *Digital Signal Processing*, 17:371–393, 2007.
- [STSH07] A. Suleiman, CM. Tojo Soler, and G. Hoogenboom. Evaluation of FAO-56 crop coefficient procedures for deficit irrigation management of cotton in a humid climate. *Agricultural Water Management*, 91(1-3):33–42, 2007.
- [Stu08] Student. The Probable Error of a Mean. *Biometrika*, 6(1):1–25, 1908.
- [SW65] S. Shapiro and M. Wilk. An Analysis of Variance Test for Normality (Complete Samples). *Biometrika*, 52(3/4):591–611, 1965.
- [Tar96] F. Tardieu. Drought perception by plants Do cells of droughted plants experience water stress? *Plant Growth Regulation*, 20(2):93–104, 1996.
- [TE91] M. Tyree and F. Ewers. The hydraulic architecture of trees and other woody plants. *New Phytologist*, 119(34):345–360, 1991.
- [TGM11] F. Tardieu, C. Granier, and B. Muller. Water deficit and growth. Co-ordinating processes without an orchestrator? *Current Opinion in Plant Biology*, 14(3):283–289, 2011.

- [The17] M. Thellier. More About the learning form of memory in plants. In *Plant Responses to Environmental Stimuli*. Springer, Dordrecht, 2017.
- [Tho72] W. Thomson. On the Equilibrium of Vapour at a Curved Surface of Liquid. *Proceedings of the Royal Society of Edinburgh*, 7:63–68, 1872.
- [Tho48] CW. Thornthwaite. An approach toward a rational classification of climate. *The Geogr. Rev.*, 38(1):55–94, 1948.
- [Tho96] JHM. Thornley. Modelling Water in Crops and Plant Ecosystems. *Ann Bot*, 77(3):261–275, 1996.
- [TL13] M. Thellier and U. Lu. Plant memory: a tentative model. *Plant Biology*, 15:1–12, 2013.
- [TLL⁺16] S. Trachsel, M. Leyva, M. Lopez, EA. Suarez, A. Mendoza, NG. Montiel, MS. Macias, J. Burgueno, and F. San Vicente. Identification of Tropical Maize Germplasm with Tolerance to Drought, Nitrogen Deficiency, and Combined Heat and Drought Stresses. *Crop Science*, 56:3031–3045, 2016.
- [TM57] CW. Thornthwaite and JR. Mather. Instructions and tables for computing potential evapotranspiration and the water balance. Technical report, Drexel Institute of Technology, Laboratory of Climatology, Philadelphia, 1957.
- [TPCW14] F. Tardieu, B. Parent, CF. Caldeira, and C. Welcker. Genetic and physiological controls of growth under water deficit. *Plant physiology*, 164(4):1628–35, 2014.
- [Tre03] A. Trewavas. Aspects of Plant Intelligence. *Annals of Botany*, 92:1–20, 2003.
- [TS66] RF. Thompson and WA. Spencer. Habituation: A model phenomenon for the study of neuronal substrates of behavior. *Physiological Review*, 73(1):16–43, 1966.
- [TSP15] F. Tardieu, T. Simonneau, and B. Parent. Modelling the coordination of the controls of stomatal aperture, transpiration, leaf growth, and abscisic acid: update and extension of the Tardieu-Davies model. *Journal of Experimental Botany*, 2015.
- [TSSA⁺13] CM. Tojo Soler, A. Suleiman, J. Anothai, I. Flitcroft, and G. Hoogenboom. Scheduling irrigation with a dynamic crop growth model and determining the relation between simulated drought stress and yield for peanut. *Irrigation Science*, 31(5):889–901, 2013.

- [Tur61] L. Turc. Évaluation des besoins en eau irrigation, l'évapotranspiration potentielle. *Ann. Agron.*, 12:13–49, 1961.
- [Tur74] NC. Turner. Stomatal Behavior and Water Status of Maize, Sorghum, and Tobacco under Field Conditions II. At low soil water potential. *Plant Physiology*, 53:360–365, 1974.
- [UDW14] UN Food and Agriculture Organization (FAO), Land Division, and Water. Municipal, Industrial, and Agricultural Water Withdrawal. In *AQUASTAT-FAO's Information System on Water and Agriculture*, page 264, 2014.
- [UL14] UN Food and Agriculture Organization (FAO) and Land and Water Division. Did you know...? Facts and Figures. In *AQUASTAT-FAO's Information System on Water and Agriculture*, 2014.
- [UM88] DR. Upchurch and JR. Mahan. Maintenance of Constant Leaf Temperature by Plants - II. Experimental Observations in Cotton. *Environmental and Experimental Botany*, 28(4):359–366, 1988.
- [UN 06] UN Food and Agriculture Organization (FAO). World reference base for soil resources 2006: A framework for international classification, correlation and communication. Technical report, UN Food and Agriculture Organization, Rome, 2006.
- [UN 09] UN Food and Agriculture Organization (FAO). Expert Meeting on How to feed the World in 2050. Technical Report 1, Rome, 2009.
- [UN 11] UN Office for Disaster Risk Reduction. Drought risks. Technical report, Geneva, 2011.
- [UN 13] UN Population Division. World population prospects: The 2012 Revision. Technical Report no. 2014, 2013.
- [URC88] SK. Upadhyaya, RH. Rand, and JR. Cooke. Role of Stomatal Oscillations on Transpiration, Assimilation and Water-Use Efficiency of Plants. *Ecological Modelling*, 41:27–40, 1988.
- [US 05] US Department of Agriculture. Crops (Chapter 3). In *National Engineering Handbook (NEH)*, pages 3/i–3/20. 2005.
- [UU75] UNESCO and UN Food and Agricultural Organization (FAO). Soil map of the World. Technical report, UNESCO, Paris, 1975.
- [VCMM+17] S. Violet-Chabrand, JSA. Matthews, L. McAusland, MR. Blatt, H. Griffiths, and T. Lawson. Temporal Dynamics of Stomatal Behavior: Modeling and Implications for Photosynthesis and Water Use. *Plant Physiology*, 174(6):603–613, 2017.

- [vdTVR09] C. van der Tol, W. Verhoef, and A. Rosema. A model for chlorophyll fluorescence and photosynthesis at leaf scale. *Agricultural and Forest Meteorology*, 149(1):96–105, 2009.
- [vdW73] JD. van der Waal. *Over de Continuïteit van den Gasen Vloeïstof-toestand*. Sijthoff, Leiden, 1873.
- [VG88] J. Vos and J. Groenwold. Water relations of potato leaves, I. Diurnal changes, gradients in the canopy, and effects of leaf-insertion number, cultivar and drought. *Annals of Botany*, 62:363–371, 1988.
- [vGTM05] D. van Gool, P. Tille, and G. Moore. *Land evaluation standards for land resource mapping*. Number December. Government of Australia, Dept. of Agriculture, 3 edition, 2005.
- [VH49] FJ. Veihmeyer and AH. Hendrickson. Methods of Measuring Field Capacity and Permanent Wilting Percentage of Soils. *Soil Science*, 68(1):75–94, 1949.
- [Von68] L. Von Bertalanffy. The Meaning of General System Theory. The Quest for a General System Theory. In George Braziller, editor, *General System Theory. Foundations, Development, Applications*, pages 30–53. New York, 1968.
- [Von71] D. Von Denffer. Physiologie des Stoffwechsels, II. Das Wasser,. In Eduard Strasburger, editor, *Lehrbuch der Botanik für Hochschulen*, pages 205–223. Gustav Fischer Verlag, Stuttgart, 30 edition, 1971.
- [WA02] LE. Williams and FJ. Araujo. Correlations among Predawn Leaf, Midday Leaf, and Midday Stem Water Potential and their Correlations with other Measures of Soil and Plant Water Status in *Vitis vinifera*. *Journal of American Society Horticulture Science*, 127(3):448–454, 2002.
- [WC00] Y. Wu and DJ. Cosgrove. Adaptation of roots to low water potentials by changes in cell wall extensibility and cell wall proteins. *J Exp Bot*, 51(350):1543–1553, 2000.
- [WdCRM10] R. Wallach, N. da Costa, M. Raviv, and M. Moshelion. Development of synchronized , autonomous , and self- regulated oscillations in transpiration rate of a whole tomato plant under water stress. 61(12):3439–3449, 2010.
- [WE12] W. Weischert and W. Endlicher. *Einführung in die Klimatologie*. Gebr. Borntraeger Verlagsbuchhandlung, Berlin, Stuttgart, 8th edition, 2012.

- [Web98] AAR. Webb. Stomatal Rhythms. In P. Lumsden and A. Millar, editors, *Biological Rhythms and Photoperiodism in plants.*, pages 69–79. Bios Scientific Publishers, Oxford, 1998.
- [Wie61] N. Wiener. *Cybernetics, or control and communication in the animal and the machine.* MIT Press, 2nd edition, 1961.
- [Wil45] F. Wilcoxon. Individual comparisons by ranking methods. *Biometr. Bull.*, 1(6):80–83, 1945.
- [WK08] L. Wu and KC. Kersebaum. Modeling Water and Nitrogen Interaction Responses and Their Consequences in Crop Models. In *Response of crops to limited water: Understanding and modeling water stress effects on plant growth processes.*, pages 215–250. 2008.
- [WR96] M. Williams and E. Rastetter. Modelling the soil-plant-atmosphere continuum in a Quercus-Acer stand at Harvard Forest: the regulation of stomatal conductance by light, nitrogen and soil/plant hydraulics. *Plant, Cell & ...*, pages 911–927, 1996.
- [WVJ+14] X. Wang, M. Vignjevic, D. Jiang, S. Jacobsen, and B. Wollenweber. Improved tolerance to drought stress after anthesis due to priming before anthesis in wheat (*Triticum aestivum* L.) var. Vinjett. *Journal of Experimental Botany*, 65(22):6441–6456, 2014.
- [WY16] P. Waller and M. Yitayew. *Irrigation and Drainage Engineering.* Springer International Publishing, Heidelberg, 1st edition, 2016.
- [WYW+10] X. Wang, W. Yang, A. Wheaton, N. Cooley, and B. Moran. Automated canopy temperature estimation via infrared thermography: A first step towards automated plant water stress monitoring. *Computers and Electronics in Agriculture*, 73(1):74–83, 2010.
- [XS01] CY. Xu and VP. Singh. Evaluation and generalization of temperature-based methods for calculating evaporation. *Hydrological Processes*, 15(2):305–319, 2001.
- [YS10] X. Yin and PC. Struik. Modelling the crop: From system dynamics to systems biology. *Journal of Experimental Botany*, 61(8):2171–2183, 2010.
- [YZZ05] HM. Yang, JH. Zhang, and XY. Zhang. Regulation Mechanisms of Stomatal Oscillation. *Journal of Integrative Plant Biology (Formerly Acta Botanica Sinica)*, 47(10):1159–1172, 2005.

- [ZB04] SJ. Zwart and WGM. Bastiaanssen. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, 69(2):115–133, 2004.
- [ZP13] Q. Zhang and FJ. Pierce. *Agricultural Automation: Fundamentals and Practices*. CRC Press, Taylor & Francis Group, Boca Raton, 1st edition, 2013.
- [ZRS⁺10] U. Zimmermann, S. Rüger, O. Shapira, M. Westhoff, LH. Wegner, R. Reuss, P. Gessner, G. Zimmermann, Y. Israeli, A. Zhou, A. Schwartz, E. Bamberg, and D. Zimmermann. Effects of environmental parameters and irrigation on the turgor pressure of banana plants measured using the non-invasive, online monitoring leaf patch clamp pressure probe. *Plant Biology*, 12(3):424–436, 2010.
- [ZRW⁺08] D. Zimmermann, R. Reuss, M. Westhoff, W. Gener, P. and Bauer, E. Bamberg, FW: Bentrup, and U. Zimmermann. A novel, non-invasive, online-monitoring, versatile and easy plant-based probe for measuring leaf water status. *Journal of Experimental Botany*, 59(11):3157–3167, 2008.
- [ZTZ⁺14] D. Zhang, R. Tang, W. Zhao, B. Tang, H. Wu, K. Shao, and ZL. Li. Surface Soil Water Content Estimation from Thermal Remote Sensing based on the Temporal Variation of Land Surface Temperature. *Remote Sensing*, 6(4):3170–3187, 2014.

Intermediate results presented/published in the following conferences/journals or prepared for submission to following journals are stated as an integral part of this thesis:

Articles

- [KS17b] Kögler, F. ; Söffker, D.: Water (stress) models and deficit irrigation: System-theoretical description and causality mapping. In: *Ecologic Modeling* 363:135-156, 2017

- [KS19a] Kögler, F. ; Söffker, D.: Explorative Frequency Analysis of Leaf Temperature Behavior of Corn (zea mays) at Water Deficit. In: *Plants*, submitted (2019)

- [KS19b] Kögler, F. ; Söffker, D.: Sport for plants as a means for growth control : Water-based open-loop control of plant growth. In preparation (2019)

Workshop presentations

- [KS16] Kögler, F.; Söffker, D.: Plant System Behavior at Deficit Irrigation: Experimental Data Collection and System Dynamical Characteristics for Irrigation Control. in: Kage, H.; Sieling, K.; Francke-Weltmann, L.: (Eds.): Jahrestagung der Gesellschaft für Pflanzenbauwissenschaften e. V., Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften, Volume 28, Verlag Liddy Halm, Göttingen, Gieen, Vol. 28, 2016, pp. 36-37
- [KS17c] Kögler, F.; Söffker, D.: Frequency analysis (FA) of leaf temperature oscillations of corn (*zea Mays*) under water stress: Experimental results of infrared thermography measurements processed by explorative FA-methods (e.g. Hilbert-Huang-Transform, Phase Portrait). Deutsche Botanische Gesellschaft, Kiel, 2017, p. 116
- [KS17d] Kögler, F.; Söffker, D.: Deficit Irrigation model-based control of plant growth - Experimental modeling of the adaptability of corn to water stress. 2nd Workshop on Plant Development and Growth, Pacific Grove, CA, 2017, p. 46
- [KS17e] Kögler, F.; Söffker, D.: Frequency analysis of leaf temperature oscillations: Analysis of dynamic plant behavior for deficit irrigation applications. in: Kage, H.; Sieling, K.; Francke-Weltmann, L.: (Eds.): Jahrestagung der Gesellschaft für Pflanzenbauwissenschaften e. V., Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften, Volume 29, Verlag Liddy Halm, Göttingen, Witzenhausen, Vol. 29, 2017, pp. 88-89
- [KS18a] Kögler, F.; Söffker, D.: Steuerung des Pflanzenwachstums durch Bewässerung. 61. Jahrestagung der Gesellschaft für Pflanzenbauwissenschaften e.V, Kiel, September 25-27, 2018
- [KS18b] Owino, L.; Kögler, F.; Söffker, D.: Moisture measurement and control in germination paper: use of model predictive control to effect required moisture level. 61. Jahrestagung der Gesellschaft für Pflanzenbauwissenschaften e.V, Kiel, September 25-27, 2018

In the context of research projects at the Chair of Dynamics and Control, the following student thesis has been supervised by Friederike Kögler and Univ.-Prof. Dr.-Ing. Dirk Söffker. Developmental steps and results of the research projects and the student thesis are integrated with each other and hence are also part of this thesis.

- [Hil15] Hilkens, M.: Modellbildung und Simulation: Planung / Aufbau eines Versuchsstandes, Bachelor Thesis, May 2015
- [Zim16] Zimmermann, F.: Modellbildung und Validierung eines komplexen Systems: Versuchsstandsaufbau für die Erhebung pflanzenphysiologischer Parameter, Automatisierung der Versuchsdurchführung sowie experimentelle Bestimmung des dynamischen Verhaltens, Master Thesis, March 2016
- [Sat16] Sattler, A.: SPS-basierte Regelung und Erweiterung eines Versuchsaufbaus sowie experimentelle Modellbildung zur automatisierten Dosierung von Flüssigkeiten, Master Thesis, October 2016
- [Hil17] Hilkens, M.: Klassische und modellbasierte Regelung des Feuchtigkeitsgehaltes eines Substrates: SPS-Programmierung, experimentelle Datenerhebung und Modellbildung, Master Thesis, June 2017
- [Lin17] Lin, T.: Programmierung mit Matlab: Messdatenauswertung eines biologischen Systems, Bachelor Thesis, March 2017
- [Lin18] Lin, T.: Experimental data collection and modeling of dynamic plant system behavior, Master Thesis, January 2018
- [Alr18] Alrakhawy, M.: Messdatenanalyse mit MATLAB, Bachelor Thesis, June 2018

