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Table: 1, Fig: 1

Pioneers of Allelopathy: XVII. Udo Blum

Udo Blum

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ABSTRACT

Udo Blum had a teaching and research career of 34 years. His primary role was teaching, advising, and mentoring undergraduate and graduate students. He authored or co-authored research publications on plant-plant allelopathic interactions, air pollution biology, and salt marsh biology. He retired in 2002 and has subsequently written a three-volume retrospective analysis of his research on plant-plant allelopathic interactions involving phenolic acids. His primary research goals were to understand: (i) how cinnamic and benzoic acids released from plants into the soil affect sensitive seedlings and soil and rhizosphere microorganisms, (ii) how phenolic acids are distributed and partitioned in seedling-microbe-soil-sand systems and (iii) how their effects on sensitive seedlings are modified by abiotic soil factors (soil pH, soil moisture, soil nutrients, presence of other organic compounds) and soil processes (microbial utilization and soil sorption) in laboratory and field model systems. In 1999 he received the Molisch Award from the International Allelopathic Society for his research contributions to our understanding of Plant-plant allelopathic interactions.

Key Words: cover crop residues, phenolic acids, seedling effects, soil processes, weeds

1. PERSONAL LIFE

I was born on November 29, 1939, and my sister, Ursula, was born about 4 years later to Lydia S. and Gerhard A. Blum living at that time in Lűdenscheid, Westphalia, Germany. My father was a carpenter and my mother was a seamstress. The family emigrated from Germany to the Unites States in 1952. We settled in Indianapolis, Indiana, where my parents worked for a telephone manufacturer. My father worked in the woodshop and my mother worked on an assembly line making telephones but later took a sales job. They became citizens of the United States on November 6, 1957. I became a permanent citizen on March 6, 1958. I attended Warren Central High School and was an active member of the Warren Central High School Choir and musical theatre. Mary Ann Schriefer, my future wife, and I met while we were graduate students in the Botany and Microbiology Department of Oklahoma University in Norman, Oklahoma. Mary Ann was working on a Master of Science degree in Microbiology and I was working on a Doctor of Philosophy degree in Botany. We were married in 1968. We received our degrees in 1969 and 1968, respectively. In 1968, I accepted a 9-month teaching position in the Botany and Microbiology Department, Oklahoma University. In 1969, I

accepted a full-time teaching-research position in the Botany Department, North Carolina State University (NCSU), Raleigh, North Carolina. Our two daughters, Amy and Nicole, were born in Raleigh. We now have 1 grandchild, 3 step-grandchildren and a step-great-grandchild. In Raleigh, Mary Ann initially worked as a medical technologist and then finally as a research technician in the Microbiology, Pathology and Parasitology Department, College of Veterinary Medicine, NCSU. I retired in 2002 and Mary Ann in 2004. In retirement among other activities, I am enjoying woodworking and reading about the history of science and travel adventures.

Professor Udo Blum

2. EDUCATION

I attended Franklin College in Franklin, Indiana, and received a Bachelor of Arts with an emphasis in Biology in 1963. I attended Indiana University in Bloomington, Indiana, and received a Master of Arts in Botany in 1965. Finally, I attended Oklahoma University in Norman, Oklahoma and received, a Doctor of Philosophy in Botany with an emphasis in plant physiological ecology in 1968. While in the Botany Department at Indian University from 1963 to 1965, I worked part time for Ralph E. Cleland cross pollinating *Oenothera* (evening primrose) plants in field plots and making chromosome slides of crushed pollen grains to characterize the structures of linked rings of meiotic chromosomes resulting from the cross pollinations. At the same time, I also worked for Charles W. Hagen, Jr. extracting flowers and plant tissues and running chromatographs on the extracts to characterize the types of flavonoid pigments synthesized in different varieties of *Impatiens balsamina* L. (Jewel weed or touch-me-not). While in the Botany and Microbiology Department at Oklahoma University from 1965 to 1968, I was a teaching assistant for 2 years in general botany and then a research assistant for Elroy L. Rice. At that time Prof. Rice was investigating the plant-plant allelopathic interactions and their potential role in old-field succession in Central Oklahoma.

3. PROFESSIONAL CAREER

In 1968 I accepted a 9-month teaching appointment as Visiting Assistant Professor in the Botany and Microbiology Department of Oklahoma University, Norman, Oklahoma. In 1969, I accepted a full-time teaching-research position in the Botany Department of North Carolina State University, Raleigh, North Carolina. My initial appointment was 80 % teaching and 20 % research. Over the years my teaching appointment was never less than 60 %.

3.1. Teaching

At Oklahoma University I taught undergraduate courses in general botany and introductory plant physiology. At North Carolina State University I taught graduate courses in introductory and advanced topics in ecology, plant physiology, plant physiological ecology and root biology. In addition, I taught undergraduate courses in plant biology for science majors and introductory plant physiology. A number of these courses included laboratory sections. I also supervised undergraduate students in laboratories for general botany. The topic of allelopathy was covered in all my courses but most extensively in plant physiological ecology and root biology. I taught 1 or 2 courses each fall and spring semester over my 34-year teaching career.

3.2 Mentoring and Advising

I have served as chairman or co-chairman for 2 Master of Life Sciences, 10 Master of Science, and 14 Doctor of Philosophy degrees (15 of these 26 degrees were related to plant-plant allelopathic interactions). I have served on graduate degree Advisory Committees for students in Agricultural Engineering, Botany, Crop Science, Forest Resources, Genetics, Horticulture, Plant Pathology, Science Education and Soil Science. I

have mentored 4 undergraduate (UG) research projects (3 on plant-plant allelopathic interactions). I also advised UG students majoring in Botany and Biology.

Students for the 15 degrees and 3 UG research projects related to plant-plant allelopathic interaction were:

(i). Master of Life Sciences: M.F. Austin and K.J. Pue,

(ii). Master of Science: B.R. Dalton, L.D. Holappa, K.C. Klein, M.E. Lehman, K. Staman, R.C. Waters and A.G. White,

(iii). Doctor of Philosophy: B.R. Dalton, A.B. Hall, M. Kochhar, M.E. Lehman, J.V. Perino and J.R. Shann,

(iv). Undergraduate Students: L.J. Flint, E. Pulley and J. Wilson.

3.3. Service

I was a grant reviewer for Federal Agencies and for Scientific Journals related to environmental sciences and to plant biology. I have served as Editor, Technical Editor, and Associate Editor-in-Chief, International Journal of Biometeorology. I have served on regional, national and international committees of Scientific Societies and as session chair for scientific meetings. I have chaired Department, College and University Committees and was Acting and Interim Head of the Botany Department, North Carolina State University. I was invited and gave presentations at scientific meetings, local and regional organizations, seminars to Departments of Universities and various classes at North Carolina State University. Of the invited presentations, seminars and lectures 85 % were related to 'Plant-Plant Allelopathic Interactions'. Chronologies of selected major events in my life are given in Table 1.

Table 1. Chronology of Selected Major Events

Year	Event
1952	Family emigrated from Germany to the United States
1958	Became a permanent United States Citizen
1963	Awarded Bachelor of Arts in Biology, Franklin College, Franklin, Indiana
1965	Awarded Masters of Arts in Botany, Indiana University, Bloomington, Indiana
1968	Awarded Doctor of Philosophy in Botany, Oklahoma University, Norman, Oklahoma
	Joined the Botany and Microbiology Department of Oklahoma University as a Visiting Assistant Professor of Botany
	Elected to membership of the Oklahoma Chapter of Sigma Xi
	Awarded best paper presentation at Southwestern Association of Naturalists Meeting, Lake Texoma, Oklahoma (Topic: Allelopathy)
1969	Joined the Botany Department of North Carolina State University (NCSU) as an Assistant Professor of Botany
	Elected to Associate Member of the Graduate Faculty of NCSU
1974	Promoted to Associate Professor with tenure in the Botany Department of NCSU
1977	Elected to Full Member of the Graduate Faculty of NCSU
1980	Promoted to Professor in the Botany Department of NCSU
	Invited and participated in Working Group for Effects of Chemicals and Interactions of Terrestrial Plants and of Plants and Microbes, US Review Division of the Office of Pesticides and Toxic Substances of EPA, Oak Ridge, Tennessee

1981	Served as Associate Editor-in-Chief, International Journal of Biometeorology
	Served as Session Chair for Physiological Ecology, Annual Ecological Society of America Meeting, Bloomington, Indiana
	Served as Session Chair for 9th International Biometeorological Congress, Germany
1981-2002	Served many times as Acting Head, Botany Department of NCSU
1982-1984	Served as Technical Editor, International Journal of Biometeorology
1984	Received award entitled: Outstanding Contributions to the Development of NCSU Botany Graduate Student Scholarship, an award given by the Graduate Students of the Botany Department of NCSU
1986	Invited presentation on allelopathy/cover crop-no-till to Granville County Agricultural Extension Service, Oxford, North Carolina
1987	Invited and co-authored article on Allelopathy for a special issue of Plant and Soil
1988	Invited presentation on allelopathy/phenolic acids, Savannah River Ecology Laboratory, Aiken, South Carolina
1994-1995	Served as Interim Head, Botany Department of NCSU
1995	Invited presentation on allelopathy/phenolic acid mixtures, American Statistical Association Winter Conference, Raleigh, North Carolina
	Invited presentation on allelopathy/phenolic acids, Biology Department of University of Cincinnati, Cincinnati, Ohio
1995-1996	Served as Editor, International Journal of Biometeorology
1996	Invited Plenary Lecturer Speaker and Symposium Chair, International Allelopathy Society First World Congress, Spain
	Invited Keynote Speaker, Seminars Series on Allelopathy/cover crop-no-till, Dept. Applied Ecology and Environmental Sciences, University of Maine, Orono, Maine
	Invited Symposium presentation on allelopathy/phenolic acids, Society of Nematologists, Little Rock, Arkansas
1998	Received Honorable Mention, Outstanding Graduate Instructor, College of Agriculture and Life Science, NCSU
	Nominated for NCSU Alumni Association Distinguished Graduate Professorship Award
1999	Invited Symposium Speaker and Crossfire Discussion Panel participant, International Allelopathy Society Second World Congress, Canada
	Received the Molisch Award from the International Allelopathy Society for research contributions to Plant-plant allelopathic interactions
2002	Received award for Poster at the International Allelopathy Society Third World Congress, Japan (ref. 59)
	Retired from the Botany Department* of NCSU
2003	Appointed Professor Emeritus
2011	Published *Plant-plant allelopathic interactions: Phenolic acid, cover crops and weed emergence*. Springer Science and Business Media, Dordrecht. 200 pp.
2014	Published *Plant-plant allelopathic interactions II: Laboratory bioassays for water-soluble compounds with an emphasis on phenolic acids*. Springer Science and Business Media, Cham. 322 pp.
2019	Published *Plant-plant allelopathic interactions III: Partitioning and seedling effects of phenolic acids as related to their physicochemical and conditional properties*. Springer Science and Business Media, Cham. 503 pp.

NCSU: North Carolina State University, Raleigh; *In 2006 the name of the Botany Department changed to Plant Biology and in 2013 further changed to Plant and Microbial Biology.

3.4. Research Interest

3.4.1. Allelopathic Plant-Plant Interactions

I was first introduced to the subject of allelopathy as a graduate student at Oklahoma University, when Elroy L. Rice became my mentor. Although allelopathy research was a primary focus, I also did research in other areas (air pollution and salt marsh biology). These research areas proved very beneficial to my understanding of stress physiology and ecosystem biology required for the study of plant-plant allelopathic interactions. My laboratory and field plant-plant allelopathic interaction studies had the following goals.

(I). Laboratory: (i) To characterize and identify the mechanisms by which allelopathic compounds, specifically cinnamic and benzoic acids (e.g., ferulic acid, *p*-coumaric acid, vanillic acid, *p*-hydroxybenzoic acid) released by plants into the soil affect sensitive seedlings and soil and rhizosphere microorganisms, (ii) to determine how cinnamic and benzoic acids are distributed and partitioned in seedling-microbe-soil-sand systems and (iii) to determine how cinnamic and benzoic acids effects on sensitive seedlings are modified by abiotic soil factors (e.g., soil pH, soil moisture, soil nutrients and presence of other organic compounds) and soil processes (e.g., microbial utilization and soil sorption) using model systems.

(II). Field and Laboratory: To determine how desiccated wheat (*Triticum aestivum* L.), rye (*Secale cereal* L.), crimson clover (*Trifolium incarnatum* L.) and subterranean clover (*Trifolium subterranean* L.) cover crop residues containing cinnamic and benzoic acids affect the weed seedling emergence of ivy leaf morning-glory (*Ipomoea hederacea* L.), prickly sida (*Sida spinosa* L.), and red-root pigweed (*Amaranthus retroflexus* L.) in a no-till agroecosystem. See a summary of results for the plant-plant allelopathic interaction studies in Sect. 4.

3.4.2. Other Research Areas

The goals of my air pollution and salt marsh research were the following:

(i). Air Pollution Biology: To determine the effects of ozone on legume growth and development, carbon allocation, nodulation, and/or nitrogen fixation. We used bush and kidney bean (*Phaseolus vulgaris* L.), soybean (*Glycine max* (L.) Mer.) and ladino clover (*Trifolium repens* L.) for this research. To determine the effects of ozone on fescue (*Festuca arundinacea*)-ladino clover (*Trifolium repens* L.) forage production and quality, population dynamics, plant-plant interactions and nitrogen fixation.

In the laboratory ozone exposures reduced the photosynthesis, total non-structural carbohydrates, amino acids, mineral content, nodulation, and root and shoot dry weights of legume plants (67,68,73). The reduction of root growth and nodulation was due to reduced translocation of carbon compounds to roots (65). The effects varied with ozone concentration and the stage of life cycle of a plant (68). When clover seedlings were grown

in fescue seedling root exudates without ozone, nodulation was stimulated (37). In the field ozone was more harmful to ladino clover than to tall fescue (64) and reduced nitrogen fixation of ladino clover (71). Ozone reduced the yield and quality of fescue-clover forage (64). Increasing ozone will further destabilize the tall fescue-ladino clover forage system.

(ii). Salt Marsh Biology: To measure *Spartina alterniflora* Loisel. (smooth cordgrass) and *Juncus roemerianus* Scheele (black needle rush) photosynthesis and respiration under field conditions and to develop a carbon and energy budget for *Spartina alterniflora* salt marshes in Brunswick County, North Carolina. To determine how various environmental factors (e.g., photoperiod, temperature, salinity, and pH) affect *Spartina* growth and development under laboratory conditions.

For *Spartina* salt marshes in North Carolina 31 % of gross primary production was respired by *Spartina* and benthic microalgae. Microbial respiration used 50 % of net primary production (gross – respiration; [66,69]). Meiofaunal and macrofaunal respiration was 8 %. About 42 % of the net primary production was exported (1/3 as dissolved organic carbon and 2/3 as particulate matter). A portion of particulate matter was lost to the marsh sediment as accretion. In the laboratory there were significant interactions between the effects of pH and salinity (70). Maximum growth occurred at pH 6 and 15 % salinity. As salinity increased, K, Ca, Mg, Na, and Cl tissue concentrations increased, but P concentration decreased. The tissue nutrient concentrations varied with treatment pH. Seedlings of *Spartina* produced maximal biomass under long-day conditions at a day/night temperature of 30/26 ^{o}C (72). The proportion of rhizome biomass for plants was greater under short-days than long-days and soluble carbohydrate was lower under long-days than short-days. Starch content in rhizomes was higher under short-days than long-days. *Spartina* marshes maintain water quality, protect against shoreline erosion, and provide nursery and essential habitat for commercial and recreational fisheries.

4. ALLELOPATHY RELATED RESEARCH

4.1. Effects of Gallotannins and Gallic Acid on Legume Nodulation

For my dissertation I determined the effects of tannic acid (actually gallotannins composed of derivatives of gallic acid bound to glucose) and gallic acid (a benzoic acid) on legume nodulation and characterized the distribution of gallotannins in soils underneath sumac (*Rhus copallina* L.) (17). I found that under the appropriate conditions (e.g., concentration and pH) gallotannins and gallic acid inhibited nodulation and reduced nodule leghemoglobin content (an indicator of potential nitrogen fixation) of red kidney bean plants (*Phaseolus vulgaris* L. my model legume species). I also found that gallotannin resistant strains of *Rhizobium* selected from commercial strains of *Rhizobium* were not as effective as the commercial strains of *Rhizobium* in producing nodules on bean plants. Others had previously found that, (i) highly eroded abandoned old-farm fields throughout Oklahoma were low in available soil nitrogen and phosphorous, (ii) the pattern and speed of revegetation of these abandoned old-farm fields were frequently determined by the levels of available nitrogen in the soil and (iii) one major natural source of nitrogen

in these fields was legume nitrogen fixation (see 17). The results of my research suggested that the presence of sumac shrubs found in such fields as well as prostrate spurge (*Euphorbia supina* Raf.), an early successional weed species that also releases gallotannins into the soil, may partly be responsible for slowing succession in such fields and the ultimate formation of prairie climax communities.

Soil samples taken from underneath sumac and prostrate spurge also inhibited the nodulation and nodule leghemoglobin content of red kidney bean plants. Gallotannins which are very water soluble were found up to a depth of 75 cm in the soil underneath sumac with a definite zone of accumulation at 35 to 55 cm depth (17). The techniques used at the time to recover and quantify gallotannins in soil were rudimentary. Amounts below 400 ppm added to soil could not be recovered even though concentrations as low as 33 ppm added to soil reduced nodulation of red kidney bean. These observations and their implications to plant-plant allelopathic interactions intrigued me. Hence, I made a promise to myself that I would take another look at this subject in the future. Around 1980 I was ready to fulfill that promise.

4.2. Inhibitory Effects of Benzoic and Cinnamic Acids on Sensitive Seedlings

Cinnamic and benzoic acids have frequently been implicated in plant-plant allelopathic interactions. The available data sets in the 1980's for effects of these acids on sensitive species were generated by bioassays using different species, a broad range of different environments and a variety of methods and protocols (for references see 61). In other words, there were lots of independent data sets that provided insight or direction for further research but lacked sufficient interconnections for creating a comprehensive understanding of how, when, and under what circumstances phenolic acids such as the cinnamic and benzoic acids negatively affected sensitive seedlings. What was, thus, needed was an in-depth quantitative approach carried out under defined environmental conditions utilizing a consistent set of components, a single model species, and a set of consistent experimental protocols and methods. We chose 4-cinnamic acids (caffeic acid, ferulic acid, *p*-coumaric acid, sinapic acid (63), 4-benzoic acids (*p*-hydroxybenzoic acid, protocatechuic acid, syringic acid, vanillic acid (63), Hoagland's nutrient solutions (61), Cecil A and B horizon soils from the Piedmont of North Carolina and Portsmouth A and B horizon soils from the Coastal Plain of North Carolina (28) and cucumber seedlings (*Cucumis sativus* "Early Green Cluster") as bioassay species (6) in our laboratory model systems. We also used other species in our model systems (bean, corn, morning-glory, pigweed, and tomato).

We found phenolic acids were readily absorbed by roots (8,9,41,44,48,49), small amounts were transported in the xylem to the shoots, and some were used in lignin synthesis (49). Data suggested that root contact, not uptake, was responsible for the inhibitory activity of phenolic acids (41). The primary site of actions for simple phenolic acids appeared to be the root cell membrane (61,63). Phenolic acid at appropriate concentration and pH reduced water use (7,8,9,10,34,43), transpiration (7,9), nutrient uptake (1,24,40,41,43,44), leaf area expansion (5,7,8,9,10,16,20,29,35,36,42), biomass

(7,8,13,16,30,45,46,47) and reproduction (51) of sensitive seedlings and/or mature plants. Effects of phenolic acids on seedlings varied with plant species (61), phenolic acid (Note: Cinnamic acids were more inhibitory than their equivalent benzoic acids), phenolic acid concentration (5,6,7,8,9,13,16,24,29,34,41,42,44,45,48,49) and plant process (6,9,16). The greater the root surface area contacted by phenolic acids, the greater the effects (35,41,42,43). Inhibition by phenolic acids increased when treatment solution acidity was increased and declined when acidity of the treatment solution was reduced (6,8,11,41,48,63). Maximum inhibition of phenolic acids occurred when the pH was below the pK_a of a phenolic acid (Note: Cinnamic and benzoic acids are monoprotic acids). In solution, the ratio of neutral and negative molecules for a given phenolic acid is determined by the pK_a of the phenolic acid and the solution pH [61,63]). The neutral molecules of a phenolic acid are the active form that interacts with root cell membranes and are absorbed by roots (63). Inhibition was also directly related to the hydrophobicity of a phenolic acid (63). Effects of phenolic acids were local, not systemic (61). As phenolic acid concentrations decreased, seedling processes recovered except for fixed morphological or anatomical characteristics (5,7,9,16). Note: Effects of phenolic acids may be stimulatory for some seedling processes while being inhibitory for others (16,49).

Microorganisms in the soil readily utilized both neutral and negative phenolic acid molecules as a carbon and/or energy source. Phenolic acid treatments below inhibitory levels stimulated the phenolic acid-utilizing microbial populations in nutrient and soil solutions, the bulk soil, the rhizosphere and the rhizoplane (18,20,45,46,57,61,63). Microbial responses varied with phenolic acid, its concentration, soil type, soil pH, soil nutrients and microbial type (e.g., actinomycetes, bacteria, or fungi (18,20,46,50,60,61, 63).

Soil sorption of neutral and negative phenolic acid molecules varied with phenolic acid, its concentration, soil type, soil pH, and the types and amounts of multivalent cations present in the soil (3,4,23,25,26,27,28,61,63). After addition, sorption of cinnamic acids occurred in two phases, (i) immediate fast sorption and (ii) slow sorption over time (23,63). Sorption of benzoic acids occurred only immediately after their addition (23,63). Sorption occurred in two forms, irreversible and reversible sorption (4,23,61,63). Phenolic acids reversibly sorbed declined as the concentration of phenolic acids in the soil solution decreased (4). Potential root available phenolic acids in the soil consist of the phenolic acids in the soil solution and those that are reversibly sorbed to soil particles (4,61,63).

Since effects of phenolic acids on sensitive seedling processes were concentration and pH dependent and inhibited seedling processes recovered as active concentrations declined, we estimated how phenolic acid molecules were quantitatively partitioned in seedling-microbe-soil-sand systems (63). As expected, the allocations to soil elements such as soil particles, soil and rhizosphere microbes and roots were highly variable depending on soil type, soil pH, soil water content, soil nutrients, types and numbers of phenolic acid-utilizing microbes, age of seedling, frequency of treatments, etc. This was the first attempt to quantitatively estimate how phenolic acids were partitioned to soil

particles, soil microorganisms and roots and how soil solution concentrations changed over time in seedling-microbe-soil-sand systems (63).

4.3. Effects of Mixtures of Phenolic Acids and Other Organic Compounds

Organic compounds released by leaf leachates (37,38), root exudates (37) and from litter and plant residues (32,33,39,50,52) into the soil consist of a range of organic compounds including phenolic acids that function as promoter/modifier/inhibitor complexes (61,63). Depending on what dominates, observed effects can be stimulatory or inhibitory. Thus, we tested mixtures of phenolic acids (i.e., cinnamic and benzoic acids (2,4,6,7,11,29,30,42,44), mixtures of phenolic acids and other organic compounds (2,13,45), plant residues containing phenolic acids (32,33,39,50,52) and a simulated phenolic acid mixture based on soil extracts (12) under laboratory conditions. We found that (i) inhibitory effects of individual phenolic acids in a mixture of phenolic acids were additive or partially antagonistic (11,29,30,42,44), (ii) mixtures composed of very low individual non-inhibitory concentrations of cinnamic and benzoic acids at the appropriate total concentration and pH were inhibitory (2,61), (iii) preferential use of organic compounds other than phenolic acids by microorganisms reduced the concentration of a phenolic acid required for a given percent inhibition (13,45) and (iv) effects of inhibitory concentrations of organic compounds other than phenolic acids plus inhibitory concentrations of phenolic acids were additive or partially antagonistic (13,45).

4.4. The Role of Modifiers

Determining the potential effects of phenolic acids was even more complicated due to differences in abiotic and biotic modifiers (i.e., soil elements, factors and processes) of laboratory and field soil systems (21,57,58). These included soil or soil solution pH (6,8,11,21,41,48), soil water content (10), soil nutrient content (36,39,60), residue nutrient content (32,33), soil and rhizosphere microbial populations (20,46,50,57,60), preferences in the use of organic compounds by microorganisms (4,45) and soil sorption of phenolic acids (25,26,27,28,61,63). They also included changes in sensitivity of seedlings after pretreatment stresses (e.g., phenolic acid stress, drought stress, and nutrient stress [40]). These modifiers directly or indirectly reduced inhibition or in some cases increased the inhibition.

The bottom line, laboratory bioassays provide little insight as to what role, if any, phenolic acids, i.e., cinnamic and benzoic acids, may actually have in plant-plant allelopathic interactions for any given managed or natural plant-soil field system since it is impossible to recreate their exact abiotic and biotic environments in the laboratory. However, they allow researchers (i) to identify the primary site or sites of action of phenolic acids at the molecular, cellular, or tissue level for sensitive plants and (ii) to characterize the subsequent set of secondary and tertiary, etc. effects that follow the primary effects. In other words, identify the mechanisms and processes by which active phenolic acids in the soil influence the physiology, growth and reproduction of sensitive plants. They also allow researchers to identify and characterize, how various abiotic and

biotic soil properties and processes change the actions of phenolic acids and how one may alter soil properties and processes to minimize or enhance the phenolic acid effects.

4.5. Effects of Desiccated Cover Crops on Dicotyledonous Weed Seedling Emergence

The soil environment for field residue bioassays more closely resembles the abiotic and biotic environments of managed or natural field systems. However, such bioassays provide little, if any, direct insight regarding processes and mechanisms. Due to complexity of field systems, we can only determine the correlations or lack of correlations between available phenolic acids in residues or soil and observed effects on plants (14,15,22,39).

We chose to determine how desiccated small grain (i.e., wheat, *Triticum aestivum* L. "Coker 983" and rye, *Secale cereal* L. "Abruzzi") and clover (crimson clover, *Trifolium incarnatum* L. "Tibbee" and subterranean clover, *Trifolium subterranean* L. "Mount Barker") cover crop residues containing cinnamic and benzoic acids affect the emergence of test broadleaf weed seedlings (ivy leaf morning-glory, *Ipomoea hederacea* L., prickly sida, *Sida spinosa* L. and red-root pigweed, *Amaranthus retroflexus* L.) in Cecil A horizon soil no-till plots (15). Crops such as corn and soybean were not planted to minimize their confounding effects on weed seedling emergence. Cover crops were sown in the fall using normal agricultural practices. Weed seeds were distributed on the surface of the soil in subplots in February. Cover crops were desiccated with glyphosate in April or May. Seedling emergence was then monitored for 2 months after initial emergence. Biomass of the desiccated cover crop surface residues, total soil phenolic acid content in ferulic acid equivalents, soil nitrate-N, soil pH, soil moisture and soil temperature were monitored at various times.

Both reductions and stimulations of broadleaf weed seedling emergence were observed over time. An initial delay of weed seedling emergence in the presence of residues was common. Effects on weed species varied with weed species, cover crop residue, time of cover crop desiccation, time after desiccation, amount of surface residue biomass and year (see 15,61). Under the cover crop residues soil moisture was increased and soil temperature was reduced. Soil nitrate-N level varied with desiccated cover crop residue. Soil pH was not modified. Total phenolic acid in ferulic acid equivalents in the soil varied with the desiccated cover crop residue but remained fairly constant over time. Total phenolic acid in ferulic acid equivalents in the desiccated surface cover crop residues declined over time. The patterns of decline varied with cover crop residue (see 15,39).

To identify potential processes, mechanisms of action and environmental interactions, we determined how seedling emergence of ivy leaf morning-glory and red-root pigweed was modified by various mixtures of Cecil A horizon soil and freeze-dried and ground surface cover crop residues under a range of environmental conditions (39). Experiments were carried out in growth chambers. For pros and cons of such residue bioassays see reference 55. Surface residues were collected from field plots before and at various times after desiccation. Data from the resulting bioassays demonstrated that seedling emergence of ivy leaf morning-glory and red-root pigweed

were modified differently and in complex ways by soil moisture, soil nitrogen, soil temperature, soil pH, residue concentration, type and age of desiccated residue and/or the total phenolic acid content in ferulic acid equivalents of the residues (see 39).

We also determined the potential effects of wheat (*Triticum aestivum* L. "Southern States 555") shoot and/or root residues on weed seedling emergence under field conditions (14). Root residue stimulated the morning-glory and prickly sida seedling emergence but inhibited pigweed seedling emergence. Shoot residue had no effect on weed seedling emergence. Subsequently we found that ground and soil incorporated shoot cover crop residue reduced the red-root pigweed seedling emergence more than ground and soil incorporated root residue (50). At 10 mg/g soil residue treatment, seedling emergence of red-root pigweed was reduced by 78 % for shoot residue and by 21 % for root residue. This suggested that inadequate rain and leaching events in the field may have been responsible for the lack of inhibitory effects of wheat shoot residue on red-root pigweed emergence in the field plots.

4.6. Collaborators and Funding Sources for Plant-Plant Allelopathic Research

Such research is very complex and requires a range of expertise and required collaboration with researchers from different disciplines. Fortunately, the following researchers generously provided their expertise and helping hand.

(i). Botany: R.C. Fites, D. Robertson and T.R. Wentworth,
(ii). Crop Science: E.L. Booker, F.L. Fiscus and A.D. Worsham,
(iii). Soil Science: D.L. Hesterberg, W.A. Jackson, L.D. King, R.J. Volk and S.W. Weed,
(iv). Plant Pathology: F. Lowes, R.A. Reinert and S.R. Shafer,
(v). Statistics: C. Brownie, T.M. Gerig, and B.R. Rawlings.

In addition, thanks to B.R. Dalton my laboratory research technician, S.-W. Lyu a visiting scholar from South Korea, my graduate and undergraduate students listed under 'Mentoring and Advising' and J. Rebbeck, C.L. Bergmark a graduate student in Soil Science, J. Meier and T.E. O'Brien graduate students in Statistics, R.H. White a graduate student in Crop Science, and S.J. Horton a research assistant in Plant Pathology for their contributions.

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4.7. Review and Retrospective Analysis

After retirement, I wrote a 3-volume Review and Retrospective analysis of this research (61,62,63):

I. Blum, U. (2011) *Plant-plant allelopathic interactions. Phenolic acids, cover crops and weed emergence.* Springer Science Business Media, Dordrecht. 200 pp.

II. Blum, U. (2014) *Plant-plant allelopathic interactions II. Laboratory bioassays for water-soluble compounds with an emphasis on phenolic acids*. Springer Science Business Media, Cham. 322 pp.

III. Blum, U. (2019) *Plant-plant allelopathic interactions III. Partitioning and seedling effects of phenolic acids as related to their physicochemical and conditional properties*. Springer Science Business Media, Cham. 503 pp.

The main objectives of above Reviews and Retrospective analyses were to: (i) describe in detail and then summarize the findings of our laboratory and field bioassays (61), (ii) characterize the pros and cons of experimental procedures and methods used (62), and (iii) determine how the physicochemical and conditional properties of phenolic acids and the sinks in seedling-microbe-soil-sand systems govern the effects of phenolic acids on sensitive seedlings (63) and (iv) provide future research directions for the potential roles of individual phenolic acids, phenolic acid mixtures and phenolic acids in promoter/modifier/inhibitor complexes in natural and managed ecosystems (61,62,63).

4.8. Pros and Cons for Procedures and Methods

Since the significance and value of any experimental data depends on the procedures and methods used to obtain that data, understanding the benefits and limits of procedures and methods used are essential. We have fully described our procedures and methods for estimating leaf area expansion (8) and depletion of phenolic acids, nutrients and water from nutrient solutions and soil or soil-sand solutions by seedlings (9,10,24,41,43,48,49). We also documented the following:

(1). Extractants and methods to quantify individual and total phenolic acid concentrations in soil and residues (3,21,22,23,28,32,39,61).

(2). How to determine the:

(a). Neutral and negative fractions of phenolic acids in solutions (63),

(b). Bulk soil and rhizosphere microbial populations (18,20,46,50),

(c). Microbial utilization of phenolic acids (4,60,63),

(d). Phenolic acids irreversibly sorbed and reversibly sorbed to soil particles and available soil solution concentrations (23,60,63), and

(e). Joint actions and doses for individual phenolic acids in phenolic acid mixtures and mixtures of phenolic acid with other organic compounds (13,30,31,45).

(3). Documented the procedures for laboratory and field residue (debris) bioassays (14,15,39,50,55,61) and soil extract bioassays in the laboratory (12).

Some of the pros and cons of these procedures and methods have been alluded to previously (see Sect 4.4 and 4.5) and pros and cons of these procedures and methods are discussed in considerable detail in my volume 2. Retrospective analysis (see 55,62).

4.9. Final Observations

My dissertation and subsequent research have focused on one group of potential allelopathic compounds, phenolic acid polymers (i.e., specifically gallotannins composed

of derivatives of gallic acid bound to glucose; gallic acid is a benzoic acid) and phenolic acids such as cinnamic acids and benzoic acids. We have taken a step-by-step approach using model systems in the laboratory and the field to study their potential roles as allelopathic agents (5,14,15,17,19,54,59,61,62,63).

(i). Laboratory studies (under defined environmental conditions): We used solution culture systems or sand-solution culture systems to determine direct effects of gallotannins, cinnamic acids, benzoic acids and/or their mixtures on seeds, seedlings and mature plants. We used soil or soil-sand culture systems to determine how soil factors (e.g., nutrients, moisture, pH, other organic compounds, microbes, and soil particles) and soil processes (e.g., soil sorption and microbial utilization) modify the effects of cinnamic acids, benzoic acids and/or their mixtures on seeds, seedlings, and soil and rhizosphere microorganisms. We also determined how soil factors (e.g., temperature, moisture, and nitrogen) modify the effects of soil-incorporated desiccated surface and root cover crop residues containing cinnamic and benzoic acids on broadleaf weed seedling emergence.

(ii). Field studies: We determined how desiccated cover crop residues containing cinnamic and benzoic acids impact broadleaf weed seedling emergence in a no-till agroecosystem.

Based on these experimental approaches, we now have developed a reasonable comprehensive understanding of how, when, and under what circumstances gallotannins, cinnamic acids, and benzoic acids negatively affect sensitive seedlings and mature plants. However, the effects of gallotannins, cinnamic acids, and benzoic acids on seedlings and mature plants cannot be easily isolated or separated from the effects of other soil abiotic and biotic factors. The primary sites and mechanisms of action may be different but the secondary, tertiary, etc. effects are identical. Under field conditions we must rely on circumstantial evidence (e.g., relationships between potentially available concentrations of phenolic acids in residues or soils and plant effects) to identify the putative or supposed roles of gallotannins, cinnamic acids and benzoic acids in plant-plant allelopathic interactions. Two circumstantial examples are provided here: (i) Gallotannins released by sumac and prostrate spurge into the soil can potentially inhibit legume nitrogen fixation and be partly responsible for slowing down succession in abandoned old-farm fields. (ii) Under the appropriate environmental conditions, particularly an acidic pH, mixtures composed of very low individual non-inhibitory concentrations of cinnamic and benzoic acids released by desiccated cover crop residues into the soil can inhibit sensitive broadleaf weed seedling emergence in no-till agroecosystems as long as the total active concentration is appropriate. We have identified 7- phenolic acids (4 cinnamic acids and 3 benzoic acids) in no-till soil (22). The average total concentration of these phenolic acids in soil samples (0 -2.5 cm) taken on 4 sampling dates (July to October) for wheat residue no-till soil (12.30 $\pm$ 0.58 µg/g soil) was 165 % higher than in fallow no-till soil (i.e., no wheat residues; 4.64 $\pm$ 0.34 µg/g soil). The pH of the soil was 5.5 $\pm$ 0.05 and 5.3 $\pm$ 0.09, respectively. When inhibition occurs, the benzoic and cinnamic acids are not likely to be

the only factor but are more likely to be a subset of the total inhibitors in a promoter/modifier/inhibitor complex in the soil. Additional observations emerge from our research are:

(i). Effects of cinnamic and benzoic acids are not only concentration but also pH dependent, as they are monoprotic acids. In solution, the ratio of neutral and negative molecules for a given acid is determined by its pK_a and pH. Neutral molecules of phenolic acids are the active form that interacts with root cell membranes, the primary site of action. A cascade of secondary, tertiary, etc. effects follows the primary effects. Maximum inhibition for a given concentration occurs when the pH values are below the pK_a of an acid. For example, the neutral molecules in a ferulic acid (pK_a = 4.58) solution are approximately 90 %, 50 %, 10 % and 1 % at pH 3.58, 4.58, 5.58 and 6.58 (63). Thus, using total concentration (i.e., neutral and negative molecules) for determining the effective dose for these phenolic acids can be very misleading. The bottom line, effects of cinnamic and benzoic acids should be based on their neutral molecules not their combined neutral and negative molecules in a soil solution. Note: The pK_a values for the 8 cinnamic and benzoic acids and gallic acid range from 4.32 to 4.64 (63). For comparison, Wikipedia lists gallotannic acid under tannic acid and states that the pK_a of tannic acid, a polyphenol, is around 6 (74).

(ii). In the laboratory, inhibitory effects of a given concentration of cinnamic and benzoic acids on seedlings increased, decreased or were lost as soil abiotic and biotic elements and/or soil processes were altered or changed over time. Given the ranges and dynamics of these elements and processes in field soils, single factor laboratory dose response bioassays are unlikely to be sufficient for identifying, if and when these acids are functioning as inhibitory agents in a given field soil. In most cases, it will require a series of factorial bioassays in the laboratory and field to arrive at any reasonable level of confidence that these acids are actually involved in or responsible for the reductions in weed seedling emergence or growth in a given field soil.

(iii). Finally, in the laboratory the range of interactions observed in morning-glory and pigweed seedling emergence to abiotic elements in the presence and absence of residues suggested that the lower soil temperature, higher soil moisture and the variation in soil nitrogen caused by cover crop residues in the field were not only important regulating factors but also modifiers of phenolic acid inhibition for weed seedling emergence.

5. PUBLICATIONS

I have authored or co-authored 76 journal publications, 10 book chapters, 3 books, 58 meeting abstracts (44 related to plant-plant allelopathic interactions), and 7 major reports related to my three research areas. In addition, I have also authored 2 editions of a Plant Biology Course Pack and authored 4 editions of a Plant Biology Laboratory Manual.

Sections 5.1 to 5.3 consist of publications related to plant-plant allelopathic interactions. Section 5.4 consists of a partial listing of publications not related to allelopathy.

5.1. Journal Publications

1. Bergmark, C.L., Jackson, W.A., Volk, R.J. and Blum, U. (1992). Differential inhibition by ferulic acid of nitrate and ammonium uptake in *Zea mays* L. *Plant Physiology* **98**: 639-645.
2. Blum, U. (1996). Allelopathic interactions involving phenolic acids. *Journal of Nematology* 28: 259-267.
3. Blum, U. (1997) Benefits of citrate over EDTA for extracting phenolic acids from soils and plant debris. *Journal of Chemical Ecology* **23**: 347-362.
4. Blum, U. (1998). Effects of microbial utilization of phenolic acids and their phenolic acid breakdown products on allelopathic interactions. *Journal of Chemical Ecology* **24**: 685-708.
5. Blum, U. and Dalton, B.R. (1985). Effects of ferulic acid, an allelopathic compound, on leaf expansion of cucumber seedlings grown in nutrient culture. *Journal of Chemical Ecology*. **11**: 279-301.
6. Blum, U., Dalton, B.R. and Rawlings, J.O. (1984). Effects of ferulic acid and some of its microbial metabolic products on the radicle growth of cucumber. *Journal of Chemical Ecology* **10**: 1169-1191.
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9. Blum, U. and Gerig, T.M. (2005). Relationships between phenolic acid concentrations, transpiration, water utilization, leaf area expansion, and uptake of phenolic acids: Nutrient culture studies. *Journal of Chemical Ecology* **31**: 1907-1932.
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12. Blum, U., Gerig, T.M., Worsham, A.D., Holappa, L.D. and King, L.D. (1992). Allelopathic activity in wheat-conventional and wheat-no-till soils: Development of soil extract bioassays. *Journal of Chemical Ecology* **18**: 2191-2221.
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14. Blum, U., King, L.D. and Brownie, C. (2002). Effects of wheat residues on dicotyledonous weed emergence in a simulated no-till system. *Allelopathy Journal* **9**:159-176.
15. Blum, U., King, L.D., Gerig, T.M., Lehman, M.E. and Worsham, A.D. (1997). Effects of clover and small grain cover crops and tillage techniques on seedling emergence of some dicotyledonous weed species. *American Journal of Alternative Agriculture* **12**: 146-161.
16. Blum, U. and Rebbeck, J. (1989). Inhibition and recovery of cucumber roots given multiple treatments of ferulic acid in nutrient culture. *Journal of Chemical Ecology* **15**: 917-928.
17. Blum, U. and Rice, E.L. (1969). Inhibition of symbiotic nitrogen-fixation by gallic and tannic acid, and possible roles in old-field succession. *Bulletin of Torrey Botanical Club* 96: 531-544.

18. Blum, U. and Shafer, S.R. (1988). Microbial populations and phenolic acids in soil. *Soil Biology and Biochemistry* **20**: 793-800.
19. Blum, U., Shafer, S.R. and Lehman, M.E. (1999). Evidence for inhibitory allelopathic interactions involving phenolic acids in field soils: Concepts vs. an experimental model. *Critical Reviews in Plant Sciences* **18**: 673-693.
20. Blum, U., Staman, K.L., Flint, L.J. and Shafer, S.R. (2000). Induction and/or selection of phenolic acid-utilizing bulk-soil and rhizosphere bacteria and their influence on phenolic acid phytotoxicity. *Journal of Chemical Ecology* **26**: 2059-2078.
21. Blum, U., Weed, S.B. and Dalton, B.R. (1987). Influence of various soil factors on the effects of ferulic acid on leaf expansion of cucumber seedlings. *Plant and Soil* **98**: 111-130.
22. Blum, U., Wentworth, T.R., Klein, K., Worsham, A.D., King, L.D., Gerig, T.M. and Lyu, S.-W. (1991). Phenolic acid content of soils from wheat-no till, wheat-conventional till, and fallow-conventional till soybean cropping systems. *Journal of Chemical Ecology* **17**: 1045-1068.
23. Blum, U., Worsham, A.D., King, L.D. and Gerig, T.M. (1994). Use of water and EDTA extractions to estimate available (free and reversibly bound) phenolic acids in Cecil soils. *Journal of Chemical Ecology* **20**: 341-359.
24. Booker, F.L., Blum, U. and Fiscus, E.L. (1992). Short-term effects of ferulic acid on ion uptake and water relations in cucumber seedlings. *Journal of Experimental Botany* **43**: 649-655.
25. Dalton, B.R., Blum, U. and Weed, S.B. (1983). Allelopathic substances in ecosystems: Effectiveness of sterile soil components in altering recovery of ferulic acid. *Journal of Chemical Ecology* **9**: 1185-1201.
26. Dalton, B.R., Blum, U. and Weed, S.B. (1989). Differential sorption of exogenously applied ferulic, *p*-coumaric, *p*-hydroxybenzoic, and vanillic acids in soil. *Soil Science Society of America Journal* **53**: 757-762
27. Dalton, B.R., Blum, U. and Weed, S.B. (1989). Plant phenolic acids in soils: Sorption of ferulic acid by soil and soil components sterilized by different techniques. *Soil Biology and Biochemistry* **21**: 1011-1018.
28. Dalton, B.R., Weed, S.B. and Blum, U. (1987). Plant phenolic acids in soils: A comparison of extraction procedures. *Soil Science Society of America Journal* **51**: 1515-1521.
29. Gerig, T.M. and Blum, U. (1991). Effects of mixtures of four phenolic acids on leaf area expansion of cucumber seedlings grown in Portsmouth B_1 soil materials. *Journal of Chemical Ecology* **17**: 29-40.
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31. Gerig, T.M., Blum, U. and Meier, K. (1989). Statistical analysis of the joint inhibitory action of similar compounds. *Journal of Chemical Ecology* **15**: 2403-2412.
32. Hall, A.B., Blum, U. and Fites, R.C. (1982). Stress modification of allelopathy of *Helianthus annuus* L. debris on seed germination. *American Journal of Botany* **69**: 776-783.
33. Hall, A.B., Blum, U. and Fites, R.C. (1983). Stress modification of *Helianthus annuus* L. debris on seedling biomass production of *Amaranthus retroflexus* L. *Journal of Chemical Ecology* **9**: 1213-1222.
34. Holappa, L.D. and Blum, U. (1991). Effects of exogenously applied ferulic acid, a potential allelopathic compound, on leaf growth, water utilization, and endogenous abscisic acid levels of tomato, cucumber, and bean. *Journal of Chemical Ecology* **17**: 865-886.

35. Klein, K. and Blum, U. (1990). Inhibition of cucumber leaf expansion by ferulic acid in split-root experiments. *Journal of Chemical Ecology* **16**: 455-463.
36. Klein, K. and Blum, U. (1990). Effects of soil nitrogen level on ferulic acid inhibition of cucumber leaf expansion. *Journal of Chemical Ecology* **16**: 1371-1383.
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40. Lehman, M.E. and Blum, U. (1999). Influence of pretreatment stresses on inhibitory effects of ferulic acid, an allelopathic phenolic acid. *Journal of Chemical Ecology* **25**: 1517-1529.
41. Lehman, M.E. and Blum, U. (1999). Evaluation of ferulic acid uptake as a measurement of allelochemical dose: Effective concentration. *Journal of Chemical Ecology* **25**: 2585-2600.
42. Lehman, M.E., Blum, U. and Gerig, T.M. (1994). Simultaneous effects of ferulic and *p*-coumaric acids on cucumber leaf expansion in split-root experiments. *Journal of Chemical Ecology* **20**: 1773-1782.
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45. Pue, K.J., Blum, U., Gerig, T.M. and Shafer, S.R. (1995). Mechanism by which non-inhibitory concentrations of glucose increase inhibitory activity of *p*-coumaric acid on morning-glory seedling biomass accumulation. *Journal of Chemical Ecology* **21**: 833-847.
46. Shafer, S.R. and Blum, U. (1991). Influence of phenolic acids on microbial populations in the rhizosphere of cucumber. *Journal of Chemical Ecology* **17**: 369-389.
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48. Shann, J.R. and Blum, U. (1987). The uptake of ferulic and *p*-hydroxybenzoic acids by *Cucumis sativus*. *Phytochemistry* **26**: 2959-2964.
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50. Staman, K., Blum, U., Louws, F. and Robertson, D. (2001). Can simultaneous inhibition of seedling growth and stimulation of rhizosphere bacterial populations provide evidence for phytotoxin transfer from plant residues in the bulk soil to the rhizosphere of sensitive species? *Journal of Chemical Ecology* **27**: 807-829.
51. Waters, E.R. and Blum, U. (1987). The effects of single and multiple exposures of ferulic acid on the vegetative and reproductive growth of *Phaseolus vulgaris* BBL-290. *American Journal of Botany* **74**: 1635-1645.
52. White, R.H., Worsham, A.D. and Blum, U. (1989). Allelopathic potential of legume debris and aqueous extracts. *Weed Science* **37**: 674-679.

5.2. Book Chapters

53. Blum, U. (1986). Plants defend themselves chemically. In: *Research for Tomorrow – 1986 Yearbook of Agriculture*. (Ed. J.J. Crowley) pp. 139-142. United Stated Department of Agriculrure, Beltsville.
54. Blum, U. (1995). The value of model plant-microbe-soil systems for understanding processes associated with allelopathic interactions. In: *Allelopathy: Organisms, Processes, and Applications.* (Eds. Inderjit, K.M.M. Daskshini and F.A. Einhellig) pp. 127-131. American Chemical Society Symposium Series No. 582. American Chemical Society, Washington DC.
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56. Blum, U. (2001). Allelopathy. In: *Encyclopedia of Plant Pathology*. (Eds., O.C. Maloy and T.D. Murray) pp. 33-34. John Wiley and Sons, Inc., New York.
57. Blum, U. (2004). Fate of phenolic allelochemicals in soils: The role of soil and rhizosphere microorganisms. In: *Allelopathy: Chemistry & Modes of Action of Allelochemicals*. (Eds., F.A. Macías, J.G.C. Galindo, J.M.G. Molinillo and H. Cutler) pp. 57 -76. CRC Press, Boca Raton.
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59. Blum, U. (2007). Can data derived from field and laboratory bioassays establish the existence of allelopathic interactions in nature? In: *Allelopathy: New Concepts and Methodology*. (Eds., Y. Fujii and S. Hiradate) pp. 31-38. Science Publishers, New Hampshire.
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5.3. Books

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62. Blum, U. (2014). *Plant-plant allelopathic interactions II. Laboratory bioassays for water-soluble compounds with an emphasis on phenolic acids*. Springer Science Business Media, Cham. 322 pp.
63. Blum, U. (2019). *Plant-plant allelopathic interactions III. Partitioning and seedling effects of phenolic acids as related to their physicochemical and conditional properties*. Springer Science Business Media, Cham. 503 pp.

5.4. Journal Publications not Related to Allelopathy

64. Blum, U., Heagle, A.S., Burns, J.C. and Linthurst, R L. (1983). The effects of ozone on fescue-clover forage: Regrowth, yield and quality. *Environmental and Experimental Bot*any **23**: 121-132.
65. Blum, U. and Tingey, D.T. (1977). A study of the potential ways in which ozone could reduce root growth and nodulation of soybean. *Atmospheric Environment* **11**: 737-739.
66. Blum, U., Seneca, E.D. and Stroud, L.M. (1978). Photosynthesis and respiration of *Spartina* and *Juncus* salt marshes in North Carolina: Some models. *Estuaries* **1**: 228-238.
67. Blum, U., Smith, G.R. and Fites, R.G. (1982). Effects of multiple O_3 exposures on carbohydrate and mineral contents of ladino clover. *Environmental and Experimental Botany* **22**: 143-154.

68. Blum, U. and Heck, W.W. (1980). Effects of acute ozone exposures on snap bean at various stages of its life cycle. *Environmental and Experimental Botany* **20**: 73-85
69. Cammen, L.M., Blum, U., Seneca, E.L. and Stroud, L.M. (1982). Energy flow in a North Carolina salt marsh: A synthesis of experimental and published data. *Association of Southeastern Biologists Bulletin* **29**: 111-134.
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73. Tingey, D.T. and Blum, U. (1973). Effects of ozone on soybean nodules. *Journal of Environmental Quality* **2**: 341-342.
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