

## Plant-Plant Allelopathic Interactions II

Udo Blum

# Plant-Plant Allelopathic Interactions II

Laboratory Bioassays for Water-Soluble  
Compounds with an Emphasis on Phenolic  
Acids



Springer

Udo Blum  
Raleigh  
North Carolina  
USA

ISBN 978-3-319-04731-7      ISBN 978-3-319-04732-4 (eBook)  
DOI 10.1007/978-3-319-04732-4  
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2011922311

© Springer International Publishing Switzerland 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

*This volume is dedicated to researchers  
and their graduate students who  
are interested in studying plant-plant  
allelopathic interactions.*

# Preface

In a previous volume (Blum 2011) the author suggested that we could improve our understanding of plant-plant allelopathic interactions in the field by making laboratory bioassays more holistic. The comments and suggestions in that volume as to how to go about that were rudimentary at best. Reflections after the volume was published lead the author to conclude that a more detailed analysis of the factors making up laboratory bioassays was needed in the hope that such an analysis would provide clearer and more useful directions on how to design more holistic or more relevant laboratory bioassay systems. The more holistic being a theoretical goal and the more relevant being a more pragmatic goal.

More specifically this volume presents a detailed description and discussion of the underlying features, issues, and suppositions associated with seed and seedling laboratory bioassays presented in the earlier volume. It also continues the retrospective analysis of seed and seedling laboratory bioassays begun in the previous volume. It is, however, broader in scope and substance in that the information provided is relevant to all water-soluble compounds released to soil by putative allelopathic living plants and their litter and residues. It is ultimately an attempt to update and expand the practical guidelines for designing laboratory bioassays that have previously been provided in the literature with the hope that the designs of future seed and seedling laboratory bioassays will become more relevant to field systems. This volume like its predecessor does not provide a comprehensive review of the literature. The literature about designing and implementing laboratory bioassays of water-soluble allelopathic compounds is much too extensive for that. Standard references have been included to provide background and additional details.

Chapter 1 provides a general introduction to this volume, discusses the nature of plant-plant allelopathic interactions, describes the nature and sources of allelopathic compounds in soils, discusses the concepts of holism and reductionism as it relates to laboratory bioassays, provides a listing of benefits, limits, and common pit falls for laboratory bioassays, and answers or sets the stage for answering the following questions: (a) Why is it important to design laboratory bioassays that are more holistic or, stated in a more pragmatic way, more relevant to field environments? (b) What can be done to make laboratory bioassays more relevant to field environments? and (c) Is it always necessary to make laboratory bioassays relevant

to field environments? Chapter 2 describes and provides comments on the following basic features of laboratory bioassays: (a) biotic and physicochemical factors, (b) test materials, (c) measurements, hypotheses, experimental designs, and data analyses, and (d) basic information that should be provided for all laboratory bioassays. Chapter 3 discusses a number of issues and challenges associated with creating more relevant model laboratory bioassays including the following: treatment concentrations, mobility and transport, species density, symbiotic relationships, microorganisms, controls or references, and measurements among others. Chapter 4 describes a set of standard hypothetical laboratory bioassays that may be used to screen for stimulatory or inhibitory effects of identified putative allelopathic compounds, leachates, exudates, litter, residues, and soils. Comments regarding potential benefits and limitations of these bioassays are provided. Chapter 5 provides an abridged version of the known effects, the physicochemical and biotic factors that modify effects, and the modes of action of allelopathic compounds using phenolic acids as the model compound. Chapter 6 describes a number of standard laboratory bioassays for identifying and characterizing the modes of action by which identified putative allelopathic compounds, mixtures of allelopathic compounds, mixtures of organic and/or inorganic compounds and residues may stimulate or inhibit sensitive weed species. Five different approaches will be described: (a) bioassays for simple mixtures of identified putative allelopathic compounds, (b) bioassays for residue leachates plus or minus XAD-4 resin, (c) the application of regression analysis to data from residues and soil extract bioassays, (d) bioassays for determining the role of treatment surface area, and (e) using omics methods as tools to determine modes of action. Chapter 7 compares field systems with past and present laboratory bioassay systems, provides some thoughts on ways to minimize the impacts of atypical factors in seed and seedlings laboratory bioassays, points out which factors limit our ability to design field-relevant model systems, suggests future directions for laboratory and field research on plant-plant allelopathic interactions in a question format, and outlines the central tenets (i.e., opinions, doctrines, or principles) articulated in this volume.

Finally, this volume has been written specifically for researchers and their graduate students who are interested in studying plant-plant allelopathic interactions. The author hopes that this retrospective and at times critical analysis of past standard laboratory bioassays will provide a foundation for better and more field-relevant laboratory designs in the future.

## Reference

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

# Acknowledgments

The author wishes to thank Regina G. Belz, Mary Ann Blum, Nicole Blum, Larry F. Grand, Stephen O. Duke, Jeffrey D Weidenhamer, Leslie A Weston, A Doug Worsham, and Deyu Xie for editing, reviewing, and thoughtful and constructive comments, Amy Blum Grady for the following illustrations: Fig. 1.1, 2.1, 3.1, 4.4, and 4.5, and the Department of Plant and Microbial Biology at North Carolina State University for their support. I would like to especially acknowledge the contribution of my wife, Mary Ann, and our two daughters, Amy and Nicole, for their continued support throughout the years and for their contributions to this volume. The author also wishes to acknowledge the contributions of faculty, students, and technicians at North Carolina State University and researchers world-wide who over the years contributed to the research upon which this volume is based. Writing this volume was truly a cooperative venture. Finally, in the previous volume (see Blum 2011) under acknowledgements the author neglected to specifically acknowledge the contributions of TM Gerig, C Brownie, and JO Rawlings for statistical analysis and modeling of data described in that volume and to include FL Booker under the list of faculty members who influenced, shaped, and reshaped the author's research program in allelopathy.

## Reference

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

# Contents

|          |   |           |
|----------|---|-----------|
| <b>1</b> | <b>Background for Designing Laboratory Bioassays .....</b>                                | <b>1</b>  |
| 1.1      | Introduction .....  | 1         |
| 1.2      | Allelopathic Interactions .....   | 3         |
| 1.3      | Nature of Allelopathic Compounds .....  | 5         |
| 1.4      | Sources of Allelopathic Compounds and Modifiers in Soils .....                            | 7         |
| 1.5      | Holism and Reductionism .....   | 11        |
| 1.5.1    | Why is It Important to Design Laboratory Bioassays that are More Holistic? .....          | 14        |
| 1.5.2    | What can be Done to Make Laboratory Bioassays More Relevant to Field Environments? .....  | 15        |
| 1.5.3    | Is It Always Necessary to Make Laboratory Bioassays Relevant to Field Environments? ..... | 16        |
| 1.6      | Benefits and Limits of Laboratory Bioassay .....  | 16        |
| 1.7      | False Assumptions and Misconceptions for Laboratory Bioassays .....                       | 18        |
|          | References .....  | 21        |
| <b>2</b> | <b>Introduction to the Fundamentals of Laboratory Bioassays .....</b>                     | <b>31</b> |
| 2.1      | Factors of Bioassay Systems .....   | 31        |
| 2.1.1    | Biotic Factors .....  | 31        |
| 2.1.2    | Physicochemical Factors .....   | 35        |
| 2.1.3    | Test Materials .....  | 40        |
| 2.1.4    | Measurements .....  | 61        |
| 2.1.5    | Hypotheses, Experimental Designs, and Data Analyses .....                                 | 63        |
| 2.2      | Basic Information Required for All Bioassay Systems .....                                 | 64        |
|          | References .....  | 66        |
| <b>3</b> | <b>Some Issues and Challenges When Designing Laboratory Bioassays ....</b>                | <b>77</b> |
| 3.1      | Introduction .....  | 77        |
| 3.2      | Treatment Concentrations .....  | 79        |
| 3.2.1    | Minimum Concentrations .....  | 79        |
| 3.2.2    | Modifiers of Active/Effective Concentrations .....  | 81        |



|          |  |            |
|----------|--|------------|
| 3.2.3    | Frequency of Treatments and/or Adjustments .....                           | 90         |
| 3.2.4    | Concentration and Dose .....   | 92         |
| 3.2.5    | Serial Dilutions of Complex Mixtures .....                                 | 93         |
| 3.3      | Field Inputs and Laboratory Treatments of Water-Soluble<br>Compounds ..... | 94         |
| 3.4      | Mobility and Proximity of Compounds in Soil Media .....                    | 95         |
| 3.5      | Seed and Seedling Densities .....  | 97         |
| 3.6      | Symbiotic Relationships .....  | 98         |
| 3.7      | Soil Microorganisms (Microflora and Fauna) .....                           | 101        |
| 3.7.1    | Numbers .....  | 102        |
| 3.7.2    | Species Diversity .....  | 103        |
| 3.7.3    | Biomass .....  | 105        |
| 3.7.4    | Distribution .....   | 106        |
| 3.7.5    | Function .....   | 108        |
| 3.7.6    | Relevance to Laboratory Bioassays .....                                    | 110        |
| 3.8      | Herbivory and Disease .....  | 110        |
| 3.9      | Physicochemical Environments .....   | 111        |
| 3.10     | References or Controls .....   | 112        |
| 3.11     | Measurements .....   | 113        |
| 3.11.1   | Seeds/Seedlings/Older Plants .....   | 113        |
| 3.11.2   | Microorganisms .....   | 114        |
| 3.11.3   | Media .....  | 115        |
| 3.11.4   | General Environment .....  | 116        |
| 3.12     | Final Comments .....   | 116        |
|          | References .....   | 118        |
| <b>4</b> | <b>Hypothetical Standard Screening Bioassays .....</b>                     | <b>131</b> |
| 4.1      | Introduction .....   | 131        |
| 4.2      | Living Plants .....  | 132        |
| 4.2.1    | Solutions Used to Collect Leachates and “Root<br>Exudates Plus” .....      | 133        |
| 4.2.2    | Leaf Leachates .....   | 135        |
| 4.2.3    | “Root Exudates Plus” .....   | 144        |
| 4.2.4    | Significance .....   | 152        |
| 4.3      | Plant Litter and Residues .....  | 153        |
| 4.3.1    | Field Study .....  | 154        |
| 4.3.2    | Test Materials .....   | 159        |
| 4.3.3    | Simulated-Rain Water .....   | 159        |
| 4.3.4    | Residue Bioassays .....  | 160        |
| 4.3.5    | Residue Leachates .....  | 166        |
| 4.3.6    | Significance .....   | 170        |
| 4.4      | Field Soils .....  | 171        |
| 4.4.1    | Soil .....   | 171        |
| 4.4.2    | Soil Plus or Minus Activated Carbon .....                                  | 173        |
| 4.4.3    | Soil Extracts .....  | 175        |

|          |  |            |
|----------|--|------------|
| 4.4.4    | Significance .....   | 175        |
| 4.5      | Final Comments .....   | 176        |
|          | References .....   | 177        |
| <b>5</b> | <b>Effects, Modifiers, and Modes of Action of Allelopathic Compounds Using Phenolic Acids as Model Compounds .....</b> | <b>185</b> |
| 5.1      | Introduction .....   | 185        |
| 5.2      | Individual Compounds .....   | 188        |
| 5.2.1    | Stimulatory Effects .....  | 188        |
| 5.2.2    | Inhibitory Effects .....   | 190        |
| 5.2.3    | Modifying Factors .....  | 192        |
| 5.2.4    | Summary Comments .....   | 219        |
| 5.3      | Simple Mixtures .....  | 220        |
| 5.3.1    | Stimulation .....  | 220        |
| 5.3.2    | Inhibition .....   | 220        |
| 5.3.3    | Summary Comments .....   | 224        |
| 5.4      | Complex Mixtures .....   | 225        |
| 5.5      | Modes of Action .....  | 226        |
| 5.6      | Final Comments .....   | 227        |
|          | References .....   | 228        |
| <b>6</b> | <b>Hypothetical Cause and Effect Bioassays .....</b>   | <b>237</b> |
| 6.1      | Introduction .....   | 237        |
| 6.2      | Identified Putative Allelopathic (IPA) Organic Compounds .....   | 242        |
| 6.3      | Complex Solutions .....  | 249        |
| 6.4      | Using Regression Analyses to Relate Potential Causes with Effects .....  | 253        |
| 6.4.1    | Residues .....   | 254        |
| 6.4.2    | Soil Extracts .....  | 256        |
| 6.5      | Treatment Surface Areas .....  | 259        |
| 6.6      | Using Omics Methods as Tools .....   | 264        |
|          | References .....   | 266        |
| <b>7</b> | <b>Laboratory Model Systems and Field Systems: Some Final Thoughts .....</b>   | <b>273</b> |
| 7.1      | Introduction .....   | 273        |
| 7.2      | Comparison of Field and Present Laboratory Model Systems .....   | 274        |
| 7.2.1    | Inputs of Water-Soluble Compounds .....  | 274        |
| 7.2.2    | Losses of Water-Soluble Compounds .....  | 275        |
| 7.2.3    | Timing and Frequency of Inputs and Losses .....  | 276        |
| 7.2.4    | Treatment Surface Areas .....  | 277        |
| 7.2.5    | Microorganisms (Microflora and Fauna) .....  | 278        |
| 7.2.6    | Media .....  | 278        |
| 7.2.7    | Plant Densities .....  | 278        |
| 7.2.8    | Physicochemical Environments .....   | 279        |

|                            |   |            |
|----------------------------|---|------------|
| 7.2.9                      | Available Water-Soluble Compounds .....   | 279        |
| 7.2.10                     | Doses (Active Water-Soluble Compounds) .....  | 280        |
| 7.2.11                     | Response Times .....  | 281        |
| 7.2.12                     | Final Comment .....   | 281        |
| 7.3                        | Is the Present Criticism by Critics Regarding Plant-Plant<br>Allelopathic Interactions in the Field Credible? ..... | 281        |
| 7.4                        | Improving the Value of Laboratory Bioassay Systems .....  | 282        |
| 7.4.1                      | Bioassay Species .....  | 282        |
| 7.4.2                      | Physicochemical Environments .....  | 283        |
| 7.4.3                      | Biotic Environments .....   | 283        |
| 7.4.4                      | Treatments .....  | 283        |
| 7.5                        | Future Directions: Questions that Need Answers .....  | 285        |
| 7.6                        | Central Tenets (i.e., Opinions, Doctrines,<br>or Principles) Articulated in this Volume .....                       | 287        |
| 7.6.1                      | Plant-Plant Allelopathic Interactions .....   | 287        |
| 7.6.2                      | Laboratory Bioassay Systems .....   | 293        |
| 7.6.3                      | Personal Note .....   | 295        |
| 7.7                        | Final Comments .....  | 296        |
|                            | References .....  | 297        |
| <b>Subject Index .....</b> |   | <b>301</b> |
| <b>Author Index .....</b>  |   | <b>315</b> |

# Abbreviations

|                    |   |
|--------------------|---|
| AIW                | Average individual weight   |
| AM                 | Arbuscular mycorrhizae  |
| ATP                | Adenosine triphosphate  |
| BOA                | Benzoxazolin-2-one  |
| CFU                | Colony-forming units  |
| C/N                | Carbon/Nitrogen ratio   |
| DIBOA              | 2,4 dihydroxy-1,4-benzoxazin-3(4H)-one                                    |
| ECM                | Ectomycorrhizae   |
| ED                 | Effective dose  |
| EDTA               | Ethylenediamine tetraacetic acid  |
| FA                 | Ferulic acid  |
| F-C                | Folin-Ciocalteu   |
| FER                | Ferulic acid  |
| GB                 | Glass beads   |
| IPA compound       | Identified putative allelopathic compound                                 |
| MES                | 2(N-morpholino)-ethanesulfonic acid                                       |
| NMR                | Nuclear magnetic resonance  |
| NPK                | N, NO <sub>3</sub> , NH <sub>4</sub> , P and K unless otherwise indicated |
| PCO                | <i>p</i> -Coumaric acid   |
| <i>p</i> C-M       | <i>p</i> -Coumaric acid and Methionine                                    |
| <i>p</i> C-G       | <i>p</i> -Coumaric acid and Glucose                                       |
| PPFD               | Photosynthetic Photon Flux Density  |
| PVP                | Polyvinylporrolidone  |
| PVPP               | Polyvinylpolyporrolidone  |
| R                  | Reference   |
| VA                 | Vanillic acid   |
| XAD or XAD-4 resin | Amberlite XAD polymeric absorbent   |

# List of Figures

|                 |  |     |
|-----------------|--|-----|
| <b>Fig. 1.1</b> | Pathways by which organic and inorganic compounds are lost from plants. (Illustration by Amy Blum Grady, used with permission) .....   | 8   |
| <b>Fig. 1.2</b> | Summary of sources, types of transport, and soil processes that determine the nature of soil solutions .....   | 10  |
| <b>Fig. 2.1</b> | Two symbiotic relationships, nodules and mycorrhizae. (Illustration by Amy Blum Grady, used with permission) .....   | 33  |
| <b>Fig. 3.1</b> | Zones for arbuscular mycorrhizae. (Illustration by Amy Blum Grady, used with permission).....  | 107 |
| <b>Fig. 4.1</b> | Field of sunflowers in Minnesota in August .....   | 135 |
| <b>Fig. 4.2</b> | Petri dish system with morningglory seeds, water, and filter paper on day one and day four.....  | 139 |
| <b>Fig. 4.3</b> | Morningglory seedlings growing in soil cup system .....  | 141 |
| <b>Fig. 4.4</b> | Stair-step system for studying recirculating “root exudates plus” leachates. (Illustration by Amy Blum Grady, used with permission) .....  | 145 |
| <b>Fig. 4.5</b> | XAD-4 resin and glass bead systems for collecting “root exudates plus” leachates. A modified version of figure by Tang and Young (1982) used with permission of American Society of Plant Biologists. (Illustration by Amy Blum Grady, used with permission) .....   | 151 |
| <b>Fig. 4.6</b> | Wheat and reference plots just before harvest in central North Carolina in June .....  | 155 |
| <b>Fig. 4.7</b> | Morningglory ( <i>top</i> ), pigweed ( <i>middle</i> ), and prickly sida ( <i>bottom</i> ) seedlings in wheat residue field subplots in July. ( <i>middle</i> and <i>bottom</i> figures taken from Blum (2011), figures used with permission of Springer Science and Business Media) .....                             | 156 |
| <b>Fig. 5.1</b> | Some common simple plant phenolic acids, cinnamic acid derivatives on the <i>right</i> and benzoic acid derivatives on the <i>left</i> , where H equals hydrogen, OH equals hydroxy, and OMe equals methoxy. (Figure taken from Blum (2011), figure used with permission of Springer Science and Business Media) ..... | 187 |

|                 |  |     |
|-----------------|--|-----|
| <b>Fig. 5.2</b> | Effects on absolute and relative rates of leaf expansion of cucumber seedlings grown in solution culture given a single 0, 0.25, 0.5 or 1 mM ferulic acid or <i>p</i> -coumaric acid treatment on day 16. All treatment solutions were replaced on day 18 with nutrient solutions. Seedlings were grown in Hoagland's nutrient solution plus or minus phenolic acids and 5 mM MES buffer. The pH values of the initial treatment solutions were 5.5, 6.25, or 7.0 ( $N=3$ ). Points are connected only to aid in the visualization of patterns over time. (Figure taken from Blum et al. (1985b). Plenum Publishing Corporation, figure used with permission of Springer Science and Business Media) ..... | 194 |
| <b>Fig. 5.3</b> | Effects on water utilization of cucumber seedlings grown in solution culture given a single 0, 0.25, 0.5 or 1 mM ferulic acid or <i>p</i> -coumaric acid treatment on day 16. All treatment solutions were replaced on day 18 with nutrient solutions. Seedlings were grown in Hoagland's nutrient solution plus or minus phenolic acids and 5 mM MES buffer. The pH values of the initial treatment solutions were 5.5, 6.25, or 7.0 ( $N=3$ ). Points are connected only to aid in the visualization of patterns over time. (Figure taken from Blum et al. (1985b). Plenum Publishing Corporation, figure used with permission of Springer Science and Business Media) .....                             | 198 |
| <b>Fig. 5.4</b> | Percent inhibition of net phosphorus (Pi) uptake by cucumber roots given a 5 h treatment of ferulic acid in solution culture when 12 days old. Treatment solutions contained ferulic acid (0.25, 0.5 or 0.75 mM), 0.5 mM $\text{CaSO}_4$ , 5 mM MES buffer, and 0.5 mM $\text{KH}_2\text{PO}_4$ . Regression models: pH 4.5 = not significant, pH 5.5 $r^2=0.71$ , and pH 6.5 $r^2=0.45$ . Based on figure from Lehman and Blum (1999b). (Plenum Publishing Corporation, data derived from figure used with permission of Springer Science and Business Media) .....   | 200 |
| <b>Fig. 5.5</b> | Percent distribution of total ferulic acid equivalents in cucumber seedlings exposed for 5 h to 5 mM plus [U-ring $^{14}\text{C}$ ] labeled ferulic acid. Equivalents were based on the specific activity of the treatment solutions. For details regarding treatment solutions see text. Mean seedling dry weights for 8 day-old seedlings were (a) roots = 30 mg, stem = 20 mg, cotyledons = 40 mg, and leaves = 110 mg and for 18 day old seedlings (b) roots = 90 mg, stem = 50 mg, cotyledons = 50 mg, and leaves = 200 mg. (Figures based on data from Shann and Blum (1987b). Pergamom Journals Ltd., data used with permission of Elsevier B.V.) .....   | 202 |

|                 |   |     |
|-----------------|---|-----|
| <b>Fig. 5.6</b> | Effects of a 7-phenolic acid mixture modeled after phenolic acids found in no-till wheat-soybean soil extracts (pH 5) on radicle and hypocotyl lengths of crimson clover as modified by polyethylene glycol (a; $r^2=0.61$ ) and Hoagland's solution (b; $r^2=0.37$ ) based on freezing-point depression (milliosmoles, mOsm) of solutions. The 7-phenolic acid mixture was composed of 10% caffeic acid, 9% ferulic acid, 35% <i>p</i> -coumaric acid, 15% <i>p</i> -hydroxybenzoic acid, 4% sinapic acid, 10% syringic acid, and 17% vanillic acid. Figures originally based on regressions from Blum et al. (1992). Plenum Publishing Corporation, regressions used with permission of Springer Science and Business Media. (Figure taken from Blum (2011), figure used with permission of Springer Science and Business Media)..... | 206 |
| <b>Fig. 5.7</b> | Changes in net phosphorus uptake (a; $r^2=0.52$ ), net water uptake (b; $r^2=0.19$ ), and absolute growth rates of leaf expansion (b; $r^2$ for FER = 0.76 and PCO = 0.58) of 13–15 day-old cucumber seedlings grown in nutrient culture as the proportion of the root systems in contact with a phenolic acid was increased, where FER equals 0.5 mM ferulic acid and PCO equals 0.5 mM <i>p</i> -coumaric acid. Figures originally based on regressions from Lyu and Blum (1990; a, net phosphorus uptake; b, water utilization) and Lehman et al. (1994; b, leaf expansion). Plenum Publishing Corporation, regressions used with permission of Springer Science and Business Media. (Figure taken from Blum (2011), figure used with permission of Springer Science and Business Media) .....                                       | 208 |
| <b>Fig. 5.8</b> | Percent inhibition of <i>p</i> -coumaric acid treatments (day 6, 8, and 10) on transpiration, water utilization, leaf area, and absolute and relative rates of leaf expansion of cucumber seedlings growing in nutrient culture (pH 5.0). The reference (or baseline) values for untreated seedlings are presented in Fig. 5.9. (Figures taken from Blum and Gerig (2005). Figures used with permission of Springer Science and Business Media).....  | 214 |
| <b>Fig. 5.9</b> | Transpiration (ml/cm <sup>2</sup> /hr), water utilization (ml/seedling/hr), leaf area (cm <sup>2</sup> ), and absolute (cm <sup>2</sup> /seedling/24 h) and relative (cm <sup>2</sup> /cm <sup>2</sup> /24 h) rates of leaf expansion of cucumber seedlings growing in nutrient culture (pH 5.0) in the absence of phenolic acids. Means and standard errors in the figures were derived from parsimonious models of Blum and Gerig (2005). Absence of standard error bars indicates that error bars are smaller than the symbols representing the means. Means and standard errors used with permission of Springer Science and Business Media .....   | 215 |

|                  |  |     |
|------------------|--|-----|
| <b>Fig. 5.10</b> | Percent inhibition of <i>p</i> -coumaric acid treatments (day 6, 8, and 10) on shoot and root dry weights (g) of 12 day-old cucumber seedlings grown in Hoagland's nutrient culture (pH 5.0). Shoot and root dry weights of untreated seedlings were $0.123 \pm 0.006$ and $0.031 \pm 0.002$ g, respectively. Percent inhibition in figure for shoot ( $r^2=0.66$ ) and root ( $r^2=0.47$ ) dry weight was derived from parsimonious models of Blum and Gerig (2005). Models were used with permission of Springer Science and Business Media.....                         | 216 |
| <b>Fig. 5.11</b> | Concentrations for each phenolic acid ( <i>one</i> ), any combination of two and three phenolic acids, and a combination of all four phenolic acids required for an approximate 30% inhibition of absolute rates of leaf expansion for 8–18 day-old cucumber seedlings grown in Portsmouth B soil materials . (Figure taken from Blum (1996). Figure used with permission of Society of Nematologists) .....   | 222 |
| <b>Fig. 5.12</b> | Concentrations of <i>p</i> -coumaric acid and methionine ( <b>a</b> ), and <i>p</i> -coumaric acid and glucose ( <b>b</b> ) required to inhibit dry weight of morningglory seedlings growing in Portsmouth B and Cecil B soils, respectively, by 10–50%. Figures adapted/replicated from ( <b>a</b> ) Blum et al. (1993) and ( <b>b</b> ) Pue et al. (1995). Plenum Publishing Corporation, figures used with permission of Springer Science and Business Media. (Figure taken from Blum (2011), figure used with permission of Springer Science and Business Media) ..... | 223 |
| <b>Fig. 6.1</b>  | An example of a nutrient-solution culture system. For this example, cucumber seedlings were treated with different concentrations of vanillic acid which were given 4 times on alternate days starting with day 8.....   | 244 |
| <b>Fig. 6.2</b>  | Light banks with cucumber seedlings growing in nutrient-solution culture. (Figure taken from Blum (2011), figure used with permission of Springer Science and Business Media) .....  | 245 |
| <b>Fig. 6.3</b>  | An example of a split-root system containing a cucumber seedling. (Bottom figure taken from Blum (2011), figure used with permission of Springer Science and Business Media) .....   | 260 |



# List of Tables

|                  |  |     |
|------------------|--|-----|
| <b>Table 3.1</b> | Some examples of potential modifiers of active/effective concentrations of water-soluble identified putative allelopathic (IPA) compounds in the absence of microorganisms .....   | 83  |
| <b>Table 3.2</b> | Some examples of potential modifying actions of microorganisms on active/effective concentrations of water-soluble identified putative allelopathic (IPA) compounds .....  | 84  |
| <b>Table 5.1</b> | Relative potencies and standard errors for effects of <i>p</i> -coumaric acid, <i>p</i> -hydroxybenzoic acid, and vanillic acid compared to ferulic acid for transpiration, water utilization, leaf area, absolute and relative rates of leaf expansion, and shoot and root dry weights of cucumber seedlings growing in nutrient culture (pH 5.2) ..... | 213 |
| <b>Table 5.2</b> | Relative potencies of sinapic acid, <i>p</i> -coumaric acid, vanillic acid, syringic acid, caffeic acid, <i>p</i> -hydroxybenzoic acid, and protocatechuic acid compared to ferulic acid for inhibition of absolute rates of leaf expansion of cucumber seedlings grown in Portsmouth soil B <sub>1</sub> soil materials (pH 5.2) .....                  | 221 |
| <b>Table 6.1</b> | Some examples of the application of omics methods to plant-plant allelopathic interactions .....   | 265 |
| <b>Table 6.2</b> | Some additional examples of how omics methods could be applied to plant-plant allelopathic interactions .....  | 265 |