THE GIST MODEL FOR SELECTION AND MODIFICATION OF SCIENTIFIC

RESEARCH FOR THE COLLEGE TEACHING LABORATORY BASED

ON ROOT COMPETITION INVESTIGATIONS

by

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through the Student Creative and Scholarly Grants that was utilized in purchasing teaching materials.

In conclusion, I would like to express my love and appreciation to my family. I was raised in an environment that has deep roots in the absolute essentiality of having strong and unwavering family values as well as the importance of education. I am extremely fortunate to have married a man who shares those same beliefs.

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ABSTRACT

THE GIST MODEL FOR SELECTION AND MODIFICATION OF SCIENTIFIC
RESEARCH FOR THE COLLEGE TEACHING LABORATORY BASED
ON ROOT COMPETITION INVESTIGATIONS

Shannon Snyder Elliott

The purpose of this study is to first develop an 8-week college teaching module

based on root competition literature. The split-root technique is adapted for the teaching

laboratory, and the Sugar Ann English pea (*Pisum sativum* var. Sugar Ann English) is

selected as the species of interest prior to designing experiments, either original or

modified, from scientific research. In each experiment, above-ground parameters, such as

the number of leaves, are recorded and graphed for each treatment, and dried root, shoot,

and flower/fruit weights are statistically analyzed. The Hotelling's T^2 test and the paired

t-test are the statistical tests employed. After instructor-testing of the experiments,

instruction is planned using the ADDIE (Analyze, Design, Develop, Implement,

Evaluate) Model and the 2 prominent theories of knowledge in science education,

objectivism and constructivism.

Next, 2 small and unreplicated field trials, using either objectivism or

constructivism as an instructional strategy, are carried out in upper-division botany

courses at the University of West Florida (UWF) with the instructor taking detailed

fieldnotes. In the objectivist-trial, 5 students initially perform an experiment already instructor-tested as feasible. Students in the constructivist-field trial (24 students, 5 groups) are challenged in groups to design and test a root competition. Students in both trials are assessed through oral and written reports. In addition, students are asked to complete an evaluation form at the end of the lesson.

The information gained through creation and teaching of the root competition product and the steps taken are used to create the GIST (Goals, Investigation, Selection, and Tests) Model for selecting and modifying scientific research for the college teaching classroom. In the first stage, the instructor composes goals for the laboratory experiment. The second step involves investigation of student experiences, skill level, and coursework. The selection of a research topic and corresponding journal articles is guided by a list of criteria. The last stage, testing by the instructor, includes the time-consuming task of modifying, testing, and revising experiments from the literature. The instructor must also select an instructional design model for the remaining steps of instruction. The GIST Model needs further testing to determine its strengths and applications.

CHAPTER I

INTRODUCTION

Scientific knowledge results from careful observations, proper planning, diligent testing, reflective analysis, and constant modifications (Tobin, 1993). Scientists employing the scientific method often aim to increase or strengthen the current body of science knowledge. New assertions are met in the scientific community with probing questions and usually debated until a general consensus is reached. However, if not supported, ideas are rethought and retested with more grounded deductions again presented. Textbooks and lab manuals present or replicate this scientific knowledge discovered by the scientific community. Ideally, textbooks are constantly updated to reflect the progress made in science, and lab manuals contain experiments that model current scientific investigation when possible (Leonard & Chandler, 2003).

Scientists and science educators adapt current literature for the teaching laboratory experience realizing that there are several fundamental differences between the teaching lab and the research lab. For example, the classroom imposes more constraints than the research laboratory in terms of time, equipment, and financial assistance (Buczynski, 2007). Most college lab classes meet for a designated time block each week and for a limited number of weeks; thus, consecutive days or long-term experiments commonly preformed in the research lab are challenging to modify for the teaching lab.

In addition, many lab classrooms do not have access to the expensive equipment utilized in research labs as well as lack financial support to purchase costly supplies.

Another concern for science educators is that experiments are safe for students (Roy, 2007) and take into consideration student skill level. Consequently, experiments for the teaching laboratory are not designed for the more safety conscious, adept, experienced researcher but for the novice student at a safety and learning level appropriate to the college classroom. Range of experimental topics is also potentially limited in the teaching laboratory by the many man-hours required for preparations, staging organisms within the life cycle, and even for acquiring institution permission when live animals are investigated, thereby, indirectly encouraging some teachers to tailor experiments, when possible, for plants.

Even though there are limitations in the teaching lab, it is still essential that experiments based on recent scientific advancements be continually produced and published for several reasons. The base of scientific knowledge is believed to double every five years (Clinton, 1998), and this presents a challenge to science educators to not only stay current with scientific developments but also to keep students up-to-date. In addition, when adapted experiments are fashioned, the lecture portion of the class must be updated to provide pertinent background knowledge. Science lecture and lab sections, working as one unit, reinforce the concepts through discussion, then exploration, respectively.

A model that systematically presents the steps for designing experiments based on recent scientific advancements for the college teaching laboratory would be helpful for instructors; however, a readily available plan does not exist (Tobin, 1993). A model

might be best fashioned through documenting the actual steps taken when a teaching module is created and planned using an instructional design plan. In addition, small field trials could explore the effectiveness of diverse learning strategies, such as objectivism and constructivism.

The traditional method for teaching science, objectivism, involves lecture and lab instruction based on textbooks and manuals, respectively. The teacher, perceived as an authoritative figure, presents knowledge to students as building blocks to larger concepts and believes knowledge exists internally to the learner (Carson, 2005). Objectivist-based teaching employs experiments where the outcome is known, often referred to as a closed-ended approach.

The other teaching style, constructivism, that focuses on students performing open-ended experiments with uncertain outcomes has gained popularity over the last 20 years (Tobin, 1993). The epistemology of constructivism asserts knowledge is constructed internally through an active and messy process, where students are expected to build a knowledge base from previous knowledge, peer-constructed knowledge, and consultations and investigation. The role of the teacher is to guide students as they design experiments that test concepts and ideas (Bevevino, Dengel, & Adams, 1999).

<center>Selection of Root Competition</center>

Criteria for science topic selection must be devised to save time and to be certain a good choice is made. Anticipating the desired outcome, several selection criteria come to mind. For example, a project for laboratory adaptation should be supported by several recent journal articles that delve into a small body of knowledge; however, these articles

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must also tie into a larger body of scientific concepts appropriate for the course level and relating to lecture topics usually addressed in the class. Another criterion is easy adaptation to the classroom, meaning supplies, facilities, and equipment are affordable and accessible. In addition, the incorporation of technology, statistical analysis, and quantitative and qualitative data collection in the experiment is crucial for providing students direct experience with methods future employers and graduate schools expect them to apply. The modified experiments should also have potential for reproducibility and have room for the addition of new student-designed experiments, cornerstones of the objectivist and constructivist strategies, respectively. And, the experiment should be amenable to both the objectivist and constructivist classroom to maximize potential for teacher adoption.

A topic that ideally fits these criteria is root competition examined in the current scientific literature (Fallik, Reides, Gersani, & Novoplansky, 2003; Gersani, Abramsky, & Fallik, 1998; Gersani, Brown, O'Brien, Maina, & Abramsky, 2001; Gersani & Sachs, 1992; Maina, Brown, & Gersani, 2002;). Ideas about nutrient effects, impact of competitors, root discrimination, and habitat selection preferences are tested and represent the more specific body of knowledge addressed by the instructor/investigator; however, background knowledge expands to root systems, root development, root functions, root-shoot relationships, and root competition.

Recent root competition experiments utilize the split-root technique, a method for creating plants with two equal root masses, and thus, as an initial objective this technique must be adapted for teaching. Placement of split-root plants into different pots and in various arrangements facilitates numerous experimental designs for students, and

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investigator testing of several designs can determine whether results are reproducible. In addition, technology, statistical analysis, and quantitative and qualitative parameters can be incorporated into modified root competition experiments, and this topic is amenable to objectivist- and constructivist-based teaching.

Purpose, Design, and Research Questions

The purpose of this study is to first develop a teaching module based on root competition literature, and then, teach the lessons in two separate, small field trials, each testing a theory of knowledge and instructional design model. The information gained through creation of the teaching product and the steps taken are used to create a model for selecting and modifying scientific research for the teaching classroom. Because the purpose revolves around addressing the laboratory teaching problem of keeping students up-to-date with scientific advances, the design of this study is action research (Creswell, 2005).

The four-part study, while conceived to meet the purpose, also is planned to answer several research questions (Table 1). For example, for instructor investigation, the steps involved in the process of bringing scientific advances down to an appropriate level for the teaching laboratory are documented. For instructional design, application of the ADDIE Model to science education is explored. Questions about possible revisions are directed toward the two small, unreplicated field trials and about the needed steps of a science model for modifying research for classroom applications.

Table 1

Study Components and Related Research Questions

Component	Questions
Experimental Designs and Tests	What are the steps taken from topic selection to self-testing for modifying root competition research for student use?
Instructional Design Plan	Can the ADDIE Model be applied to planning instruction after root competition experiments are developed? Does the ADDIE Model effectively organize instruction based on two different teaching paradigms?
Field Trials	What are the teacher observations and insights for the two separate and small field trials? Taken individually, how can each trial be improved?
Science Model	Can the steps for adapting root competition experiments to the teaching laboratory be incorporated in a model useful to other instructors? If yes, what are the aims for future use of the proposed model?

Possible Benefits

Student familiarity and experimentation with new scientific research can potentially increase student interest (Burrowes, 2003). Because a major complaint among students in college science courses is that the subject is unchanging and boring (Herreid, 2006; Osborne, Simon, & Collins, 2003), new and expanding scientific knowledge might

portray the dynamic and exciting nature of science to students. Also, recent scientific research often involves technology, a student motivational tool when properly employed (Tan, Yeo, & Lim, 2005; Tobin, 1993).

Increasing student interest might attract students and cause them to select a career in science or science education. Recruitment is crucial because women are leaving science in record numbers, and the drop off increases dramatically at every educational transition, especially undergraduate to graduate school (Cavanagh, 2005; Clift, 2007). In addition, women who do select careers in science represent less than 12% of the total number of scientists and engineers in business and industry, according to the National Council for Research on Women (Terzian, 2006).

Similar to the low number of women in science, there is also a critical shortage of science teachers (Moin, Dorfield, & Schunn, 2005). Studies show that many principals struggle to find qualified science teachers and often fill the position with teachers lacking strong science backgrounds **(**Mangrubang, 2005). Many school districts, hurting for science teachers, ask foreign, veteran teachers for assistance (Hutchinson, 2006) as well as offer prospective teachers forgiveness of government loans. Research on attracting college students to science education indicates that key targets for science teacher recruitment are junior and senior level undergraduates (Moin et al.); thus, capturing student interest is especially necessary in upper-division science or education courses.

Attracting exceptional science teachers is important for national success because some predict that the degree to which students are grounded in scientific knowledge dictates the future economic success and competitiveness of the United States (Andrade, Stigall, Kappus, Ruddock, & Oburn, 2002; Gordon, 2007). Continued economic

achievement is also considered contingent upon the skill level of students entering into the scientific community (Garkov, 2002). Experimentation focusing on new ideas from the literature might have the potential to increase student skill level.

This study is geared toward conscientious educators who endeavor to improve how they develop and teach lessons, while keeping students up-to-date with recent literature and laboratory techniques. Introducing students to current research is not limited to science but has applications in other subject areas. Lastly, this study might have the greatest benefit for all science teachers who are questioning how teaching methods might be adjusted to improve student interest and achievement in science.

Remaining Chapters

While this chapter lists the research questions, the remaining chapters discuss if and how they are answered. In Chapter II, a review of instructional design, including prominent instructional design models, is followed by a discussion of the two primary theories of knowledge in science education. The latter portion of the second chapter is dedicated to background knowledge on roots including root systems, root development, root functions, root-shoot relationships, root competition, and the split-root technique. Survey of instructional design and root research are used in designing the methods for the four components of the study, discussed in Chapter III. The results and discussion of the 4 parts are found in Chapters IV and V, respectively.

CHAPTER II

REVIEW OF THE LITERATURE

Teaching or the instructional process is traditionally perceived as instructors passing knowledge in textbooks onto the learner. Of the three components, teachers, learners, and materials, improvements in this approach focus on increasing the knowledge and skills of the instructor. However, in instructional design, the instructional process is not only highly dependent upon teachers, learners, and materials, but also the learning environment as well (Dick, Carey, & Carey, 2001). Instead of improvements solely directed towards the teacher, the construction of a systematic plan with the interaction of the 4 parts is planned with desired outcomes in mind (Dick & Reiser, 1989).

Instructional Design

Besides the necessity of constructive interaction between the teachers, learners, materials, and learning environments, there are at least four other basic assumptions concerning instructional design (Gagné, Briggs, & Wager, 1992). The aim of learning should be directed toward the individual learner even if students are instructed in groups. Also, phases of instructional design range from present to long-term. Teacher preparation for the upcoming lesson plan is an example of the former, while reorganization of a course is the latter (Gagné et al.). A third assumption is that when instruction is

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systematically planned, human learning is positively affected, while unplanned instruction can have negative effects. The last point is that instructional design is performed through a systems approach where steps are outlined, starting with analysis of needs and goals of the learner and ending with evaluation and revision of the instruction (Gagné et al.).

The last assumption supports the basic definition of instructional design; it is a systematic and reflective process for deciding what and how to teach including student goals, instructional strategy selection, and evaluation (Smith & Ragan, 1999; Dick, 1995). For example, the instructional designer or teacher identifies specific skills and goals for the learner. Based on the goals and after analysis of the students, an instructional strategy using one or more theories of knowledge is developed. The strategy selected is likened to a blueprint and after implementation is then formatively evaluated. Revisions are made followed by repetition of the process with the incorporation of improvements (Dick). Congruency is essential among the goals, instructional strategies, and evaluation (Smith & Ragan).

Philosophical Basis of Instructional Design

The foundation for instructional design is based on philosophy, especially constructivism, and theory including learning, developmental, and instructional theories (Smith & Ragan, 1999). In constructivism, knowledge is assumed constructed internally by the learner not transmitted from an external source (Driscoll, 2000). Learners actively attempt to seek meaning from their new experiences and to make sense of incoming information that conflicts with previous information. In addition, knowledge construction

does not necessarily truly reflect what is occurring in the external reality (Driscoll). Constructivism can be divided into three groupings: individual, social, and contextualism (Smith & Ragan). The assumptions of individual constructivism are learning is an effortful process and is based on personal interpretation of first-hand experiences. In social constructivism, group collaboration through negotiation of meaning is stressed for learning. Learning occurring in a realistic situation as well as learning assessment incorporated into a learning project are the assumptions of contextualism. The former assumption is known as situated cognition where learning is related to a context that is meaningful and relevant (Tobin, 1993).

The tenets of constructivism have influenced many aspects of instructional design (Smith & Ragan, 1999). Constructivist principles illustrate the necessity of analyzing previous knowledge and experiences of learners. In addition, with the assertion of the tentative nature of knowledge, constructivists challenge instructional designers and teachers to develop instruction that reflects the changing character of information construction and to utilize a theory of knowledge as a guide in creation of instructional strategies. Tenets of constructivism also point to the incorporation of technology in a meaningful way, which has greatly expanded the options for instructional designers and teachers (Smith & Ragan).

Theoretical Basis of Instructional Design

In addition to philosophy, behavioral and cognitive learning theories have significantly impacted instructional design (Morrison, Ross, & Kemp, 2004). The behaviorist view of learning is focused on studying observable behaviors and the

influence of the environment on behavior. For example, B. F. Skinner depicted learning

and behavior as a black box (Driscoll, 2000). The black box represents the learner where

nothing is known about the content, but how the box or learner responds to

environmental stimuli can be predicted (Figure 1). Even though visual behaviors were the

focus of Skinner and other behaviorists, the existence of mental activity was not refuted

(Smith & Ragan, 1999).
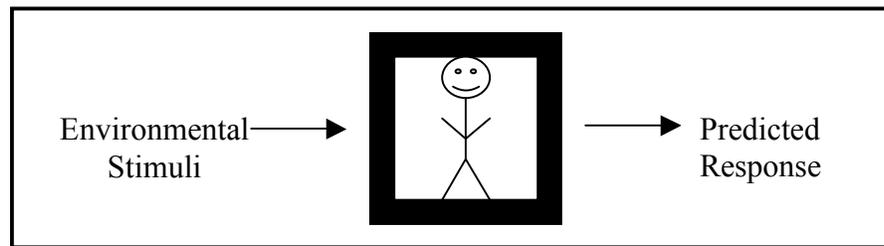
Figure 1. Essential features of the black box metaphor for the learner.

Note. Based on Driscoll, M. P. (2000). *Psychology of learning for instruction* (2nd ed.). Boston, MA: Allyn & Bacon.

While several tenets of behaviorism have not contributed to defining instructional

design, programmed instruction proposed by Skinner has a major impact (Smith &

Ragan, 1999). Through an instructional program, Skinner presents content organized in

small steps progressing from simple to more complex and at each step a correct response

by the learner is required (Ormrod, 2004). Lessons from programmed learning for

instructional design include learning that can occur through effective nonhuman,

mediated instruction and the importance of evaluation and revision in instruction (Smith

& Ragan).

While the behaviorist view of learning emphasizes observable behavior and the

influence of the environment, cognitive learning theories concentrate on factors within

the learner (Driscoll, 2000). For example, in information-processing theory, the stages of

information processing describe learning as occurring in the learner first through entering

the sensory memory from sensory input from the environment (Figure 2). The

information is processed and stored in the short-term memory, operating as a temporary

working memory. With rehearsal, information in the short-term memory can help the

learner to generate a response or with further encoding the information can be stored in

long-term memory (Driscoll). Only information that is meaningful and agrees with prior

knowledge is able to transfer to long-term memory (Driscoll). Cognitive learning

theories, such as information-processing, suggests the necessity of the instructional

designer or teacher to tap into the prior knowledge and aptitude for memory of the

students (Bonner, 1998). In addition, unlike in behaviorism, learning should be analyzed

not strictly on behavior or completion of a procedure, but by assessing mental tasks

(Bonner).
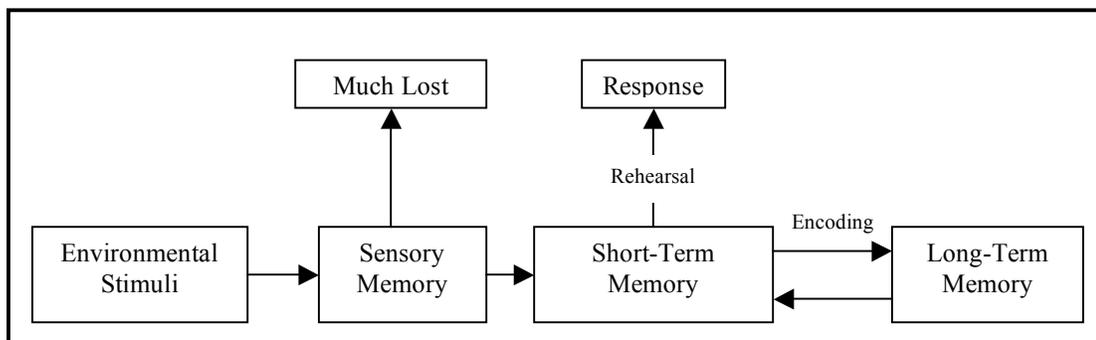
Figure 2. Basic concepts that depict the stages in learning according to the information-processing theory.

Note. Based on Ormrod, J. E. (2004). *Human learning* (4th ed.). Upper Saddle River, NJ: Pearson.

In addition to learning theories, developmental theories primarily proposed by

Jean Piaget and Lev Vygotsky have also shaped instructional design. Piaget maintained

that learners transition through four developmental stages: sensorimotor (birth to age 2),

preoperational (ages 2-7), concrete operational (ages 7-11), and formal operation periods (age 11 and on). Each step is characterized by key cognitive tasks that emerge only after a particular stage of development is reached (Piaget & Inhelder, 1969). For example, in the concrete stage, learners can solve concrete problems using logic only after they have overcome egocentric thought and communication of the preoperational stage (Driscoll, 2000).

Piaget also advanced descriptions of four cognitive learning processes: assimilation, accommodation, disequilibrium, and equilibrium (Ormrod, 2004). Assimilation and accommodation involve cognitive processes used to incorporate new knowledge and modify present cognitive information, respectively. Disequilibrium is a state of disorder experienced by the learner concerning integration of new material; however, the cognitive processes to overcome disequilibrium is equilibrium (Smith & Ragan, 1999).

Unlike Piaget, Vygotsky maintained that learning can surpass a particular developmental stage. With the assistance from a teacher, learners can tackle problem-solving tasks that they, otherwise, could not accomplish (Vygotsky, 1978). One method of help is scaffolding wherein a teacher guides to assist the students through the challenging assignment. Eventually, students acquire the necessary skills and scaffolding of that task is lessened and eventually stops. The larger range of abilities with assistance is termed the zone of proximal development (Figure 3).

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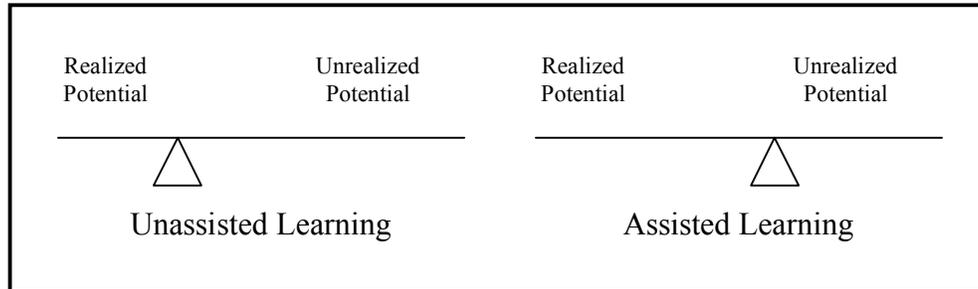
Figure 3. Interpretation of Vygotsky's Zone of Proximal Development where assisted learning promotes student development of potential.

The developmental theories of Piaget and Vygotsky have made contributions to instructional design (Smith & Ragan, 1999). For example, the instructional designer or teacher must consider the developmental stage of the learners, especially for younger learners. If the task is possibly outside the range of cognitive abilities, the teacher must question whether scaffolding is appropriate. In addition, new material needs to be organized and presented in such ways as to promote assimilation and accommodation (Smith & Ragan).

While learning and developmental theories are descriptive, the theories primarily contributing to instructional design are prescriptive theories known as instructional theory (Morrison et al., 2004). Instructional theory involves selection and identification of methods that facilitate best conditions for learning to occur (Reigeluth, 1983). An instructional theory should also address and analyze the learner, the learning task, instructional methods, and the context in which learning is to occur (Schott & Driscoll, 1997). An example of an instructional theory is Gagné's Theory on Conditions for Learning (Gagné & Medsker, 1996). Gagné proposed that instruction should activate and reflect the internal flow of information (Figure 2), and thus, listed nine crucial

instructional steps and actions starting with stimulating interest through using an

environmental stimulus (Table 2). The other instructional steps and actions also support

the internal process of learning as described by learning theories.

Table 2

Explanation of Gagné's Nine Instructional Steps and Related Occurrences in the Information-Processing Theory

Instructional Steps	Step in Information-Processing Theory
Stimulate Interest	Environmental Stimuli
State Learning Objectives	Anticipation
Evoke Prior Knowledge	Access Long-Term Memory
Deliver Instruction	Sensory- to Short-Term Memory Path
Direct Learning Process	Encode into Long-Term Memory
Draw Out Learner Responses	Rehearsal in Short-Term Memory
Reinforce Learning	Short- to Long-Term Memory Path
Evaluate Learning	Rehearsal and Encoding Repeated
Improve Retention	Merge Previous and New Information

Note. Based on Driscoll, M. P. (2000). *Psychology of learning for instruction* (2nd ed.). Boston, MA: Allyn & Bacon.

Instructional Design Models

While learning theory describes how learning occurs and instructional theory applies learning theory to define strategies for instruction, elements of both are combined to create an instructional design plan or model (Morrison et al., 2004). Most instructional design models present step-by-step procedures and are usually depicted through figures such as flow charts. However, even though this depiction might illustrate the process as linear, it is open and dynamic (Morrison et al). A typical instructional design model begins with the selection of a topic or subject followed by the composition of learning objectives used as a guide to develop instruction (Figure 4). Upon assessment of the instruction, improvements occur at any phase.
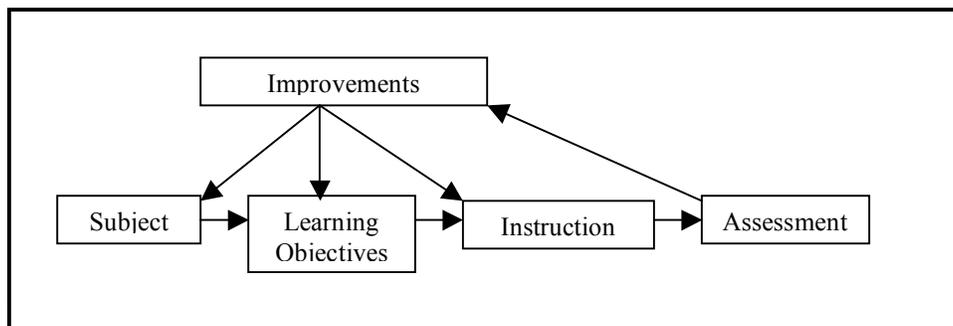
Figure 4. Features of a general instructional design model.

Note. Based on Morrison, G. R., Ross, S. M., & Kemp, J. E. (2004). *Designing effective instruction* (4th ed.). New York: John Wiley and Sons.

Adjustments are made to the general instructional design model to adapt to the teaching or business situation (Romidxowski, 1981). Examples of instructional design models are ADDIE Model and Keller's ARCS Model as well as the models advanced by Dick and Reiser, and Dick and Carey. While models differ, each designer attempts to present a framework for instruction development (Smith & Ragan, 1999).

ADDIE Model

The ADDIE Model (Analysis, Design, Development, Implementation, and Evaluation) provides instructional designers and teachers with a systematic process for developing instruction in a variety of settings (Peterson, 2003). Each stage of the model has a specific purpose, and the five steps together comprise the framework (Figure 5). In the analysis phase, student assessment is performed to establish what the learners know and what they need to know. In addition, a task analysis is conducted to determine the specific skills needed for the learners (Peterson). Elements of the design stage include identifying objectives for the learners and strategizing how to met these through instruction. Construction of a lesson and evaluation of the teaching product is the central goal of development. In the implementation phase, the instructional product is delivered with the developer or instructor continuing to improve instruction based on teacher observations and student feedback. Evaluation is crucial during the analysis, design, development, and implementation phases and the teacher must ultimately determine the appropriateness of the objectives and if they were met (Peterson).
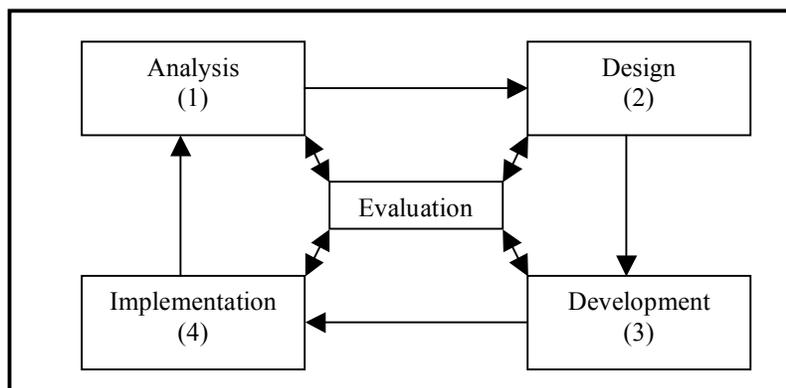
Figure 5. Interpretation of the ADDIE Model.

Note. Based on Peterson, C. (2003). Bringing ADDIE to life: Instructional design at its best. *Journal of Educational Multimedia and Hypermedia*, *12*(3), 227-241.

Keller's ARCS Model

Another instructional design plan is Keller's ARCS Model, standing for Attention, Relevance, Confidence, and Satisfaction (Keller, 1983). The ARCS model incorporates instructional theory through prescribing action for increasing motivation to learn and solve problems in the learner. Each word is a motivation category with several specific strategies; for example, a technique for grabbing and sustaining attention is inquiry where students are challenged to solve problem-based activities. A strategy for making the material relevant is to describe the current value of the instruction for the students. Building confidence in learners may be produced through attributions, students understanding their successes are based on their efforts not luck, and through positive outcomes, for instance, verbal praise given by the teacher so that the learner may leave the lesson with satisfaction (Lebow, 1995).

Keller's ARCS Model (1983) illustrates how to incorporate motivation into the instructional design process through four phases: define, design, develop, and evaluate (Figure 6). Motivational problems are identified, and motivational objectives are prepared in the define phase. In the second stage, appropriate ARCS motivational strategies are selected and integrated into instruction in the development step. Motivational outcomes are assessed and evaluated against the initial objectives in the last phase.

Define (1) Define the Motivational Problem Determine Learner Motivation Compose Motivational Objectives	**Design (2)** List Possible Motivational Strategies Analyze Motivational Strategies Select Motivational Strategies
Evaluate (4) Assess Motivational Strategies Determine Strengths and Weaknesses Suggest Improvements	**Develop (3)** Develop Instruction Incorporate Motivational Strategies Plan for Assessment

Figure 6. Diagrammatic interpretation of Keller's ARCS Model related to motivational strategies.

Note. Based on Smith, P. L., & Ragan, T. J. (1999). *Instructional Design (2nd ed.)*. New York: John Wiley & Sons.

Dick and Reiser Model

Similar to the previous models, the Dick and Reiser Model presents a systematic procedure for developing instruction (1989). The emphasis of the model centers on effective instruction, instruction where students learn skills and knowledge while enjoying lessons. The model includes the teacher setting goals for learners, selecting appropriate materials, and analyzing the learners before writing objectives (Figure 7). Next, tests or other assessment of learning are developed followed by the creation of instructional activities. The media or means of presenting the instructional activities are planned prior to the actual teaching of the lesson. Revisions are made after data collected during implementation are analyzed and the process for the lesson is repeated (Dick & Reiser). All components are carefully linked and provide a step-by-step plan for teachers.
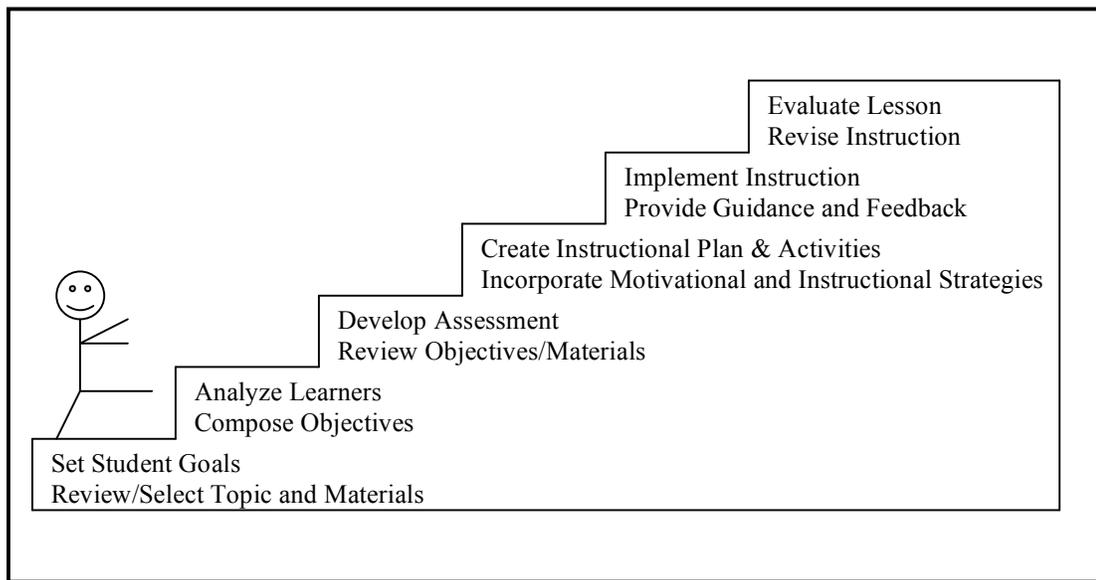
Figure 7. Depiction of the essential steps in the Dick and Reiser Instructional Design Model.

Dick and Carey Model

Like the Dick and Reiser Model, other instructional design plans such as the Dick and Carey, and Gagné Models (Dick et al., 2001; Gagné et al., 1992) can be depicted as a step-by-step process. Both models list ten components necessary for a complete instructional design plan and are very similar; thereby, only the Dick and Carey Model is discussed below in detail (Figure 8). First, the needs for the instruction are assessed, and goals for the learners are written. After the needs assessment, the skills needed by learners to perform the goals are determined, known as instructional analysis. In addition to instructional analysis, learners and the context are examined to help in writing objectives of what the students will be able to do at the end of the instruction. Assessment instruments are developed to measure learner performance in relation to the objectives.

Next, based on theories of learning and knowledge, instructional strategies are selected, and then, instructional materials developed. Formative evaluation of instruction follows, including one-to-one evaluation where the designer or teacher works with individual learners or more experienced peers to improve instruction, small group evaluation to identify learning problems missed in the previous evaluation, and field evaluation consisting of a field trial in the learning environment. Instruction is revised based on results of the formative evaluation, and after sufficient revisions, a summative evaluation is employed to examine the worth of the instruction (Dick et al.; Gagné et al.).

Summative Evaluation

Improvements

Field Trial(s)
Formative Evaluation

Selection of Instructional Strategies
Development of Instructional Materials

Composition of Objectives
Assessment Production

Needs Assessment (Instructional Goals and Learner Goals)
Instructional Analysis (Learner Skills)
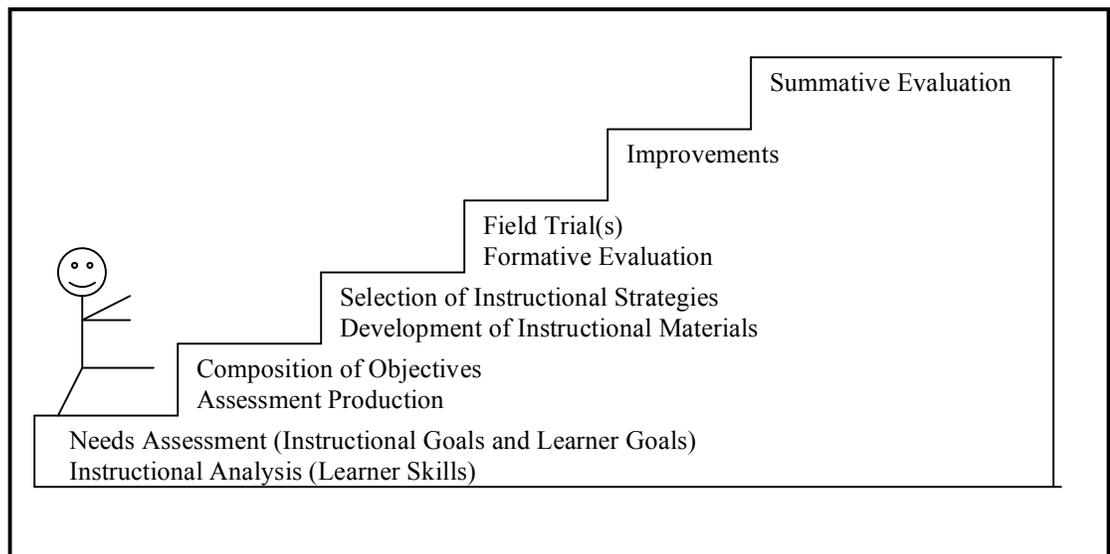
Figure 8. Depiction of the essential steps in the Dick and Carey Instructional Design Model.

Note. Based on Dick, W., Carey, L., & Carey, J. O. (2001). *The systematic design of instruction* (5th ed.). New York: Longman.

The Dick and Carey Model and other models described above, each have their advantages. The ADDIE Model, while usually applied to instructional courses and training courses, is simple and adaptable to other fields and highly desirable for instructional designers and teachers (Peterson, 2003). Keller's ARCS Model (1983)

presents steps for addressing motivational issues, and the Dick and Reiser Model is specifically geared for teachers (Dick & Reiser, 1989). Even though the Dick and Carey Model is complex, it includes nearly all possible phases and is a valuable tool for beginning designers (Dick et al., 2001).

Objectives, Instructional Strategies, and Evaluation

Although there are differences, the previous instructional design models each contain three anchoring points: objectives, instructional strategies, and evaluation (Gagné et al., 1992). To potentially create an instructional design model on how to bring new scientific research into the teaching laboratory, these three concepts must be investigated.

Crucial to an instructional design model is the necessity of formulating learning objectives to illuminate what the learner should know by the completion of the instruction. However, what constitutes an objective often needs clarification. The three components of a quality objective are performance, conditions, and criteria (Mager, 1997). The objective includes statements or pictures that state or depict the specific outcomes desired. Because many words such as "know" can be misinterpreted, specific verbs like "solve" should be employed (Mager, p. 45). In a quality objective, conditions for performance and competency level are used to help evaluate performance. An example of a quality objective is "Given a computer with word-processing software (conditions), be able to write a letter (performance). All words are spelled correctly, there are no grammatical or punctuation errors, and the addressee is not insulted (criteria)" (Mager, p. 47).

While three components are incorporated into an objective, there are characteristics that do not belong (Mager, 1997). The desired outcomes should not focus on an instructional procedure. For example, statements concerning the process of constructing a home such as "the foundation is laid first" as are not objectives; however, the outcome of the process such as "the house has four bedrooms" is a part of an objective (Mager, p. 7). In addition, an objective does not have specific formatting. The procedure, conditions, and criteria are not necessarily confined to a couple of words or sentences (Mager).

Besides objectives, another crucial phase in any instructional design plan is the selection and development of instructional strategies, which encompass how instruction is presented to the learner (Morrison et al., 2004). The application of instructional strategy is attributed to ideas behind Gagné's Theory of Conditions for Learning (Table 2). Using the instructional theory presented by Gagné as a guide, five major learning elements are part of an instructional strategy: pre-instruction activities, content presentation, learner participation, assessment, and follow-through activities (Dick et al., 2001).

The pre-instructional activities stage involves selecting and implementing motivational strategies such as the techniques proposed in the Keller's ARCS Model (Dick et al., 2001). In addition, tactics are fashioned on how to inform learners of the objectives of the instruction. Planning for content presentation includes identifying the concepts, rules, and principles of importance to learners. The third element is deciding upon how learners will participate in the instruction. Learning activities offer students the opportunity to practice skills and explore the content. The instructional designer or

teacher in the assessment stage answers whether entry behaviors are tested and when student assessment will occur (Dick et al.). Assessment of student learning can include exams that are graded with answer keys, reports examined using a rubric, and/or class presentations judged based on an outline. Follow-through activities, the last phase, is a review of the overall instructional strategy to question whether students under the conditions have the opportunities for proper learning (Dick et al.).

Along with objectives and instructional strategy, evaluation, especially formative evaluation is a consistent theme across instructional design models (Smith & Ragan, 1999). Formative evaluation is a process to obtain data and information to revise instruction (Dick et al., 2001). Even though formative evaluation encompasses informal one-to-one evaluation, and small group evaluation, as well as field testing in the actual learning context, all are not necessarily completed; however, one or more techniques should be undertaken (Dick et al.). Field trials and the data gathered during the experience are crucial evaluation tools for teachers developing instruction (Dick & Reiser, 1989). Data collected often includes observational notes taken by the teacher, especially noting any difficulties the students exhibit for possible future revisions. In addition, while pre-tests may not be given, post-tests on objectives or other assessments related to the objectives are necessary. A third area of data collection is student attitudes toward the instruction that can be obtained through student questionnaires and evaluations (Dick & Reiser). The data from several sources, data triangulation, can be systematically reviewed and coded to investigate trends related to what is going on and what could be improved (Patton, 2002).

Also important to the instructional design plan is the selection of a theory or theories of knowledge as a key component of instructional strategy. If a teacher aligns with a specific epistemology, the ideas from that approach help to guide instructional development. Educators maintain that beliefs about how students learn impact all aspects of instruction from writing objectives to evaluation (Applefield, Huber, & Moallem, 2001). Within the science classroom the dominant epistemologies that endeavor to explain how students know and learn are objectivism and constructivism.

Objectivism

Objectivism, the traditional approach, views knowledge as existing externally to the learner. The idea is that students learn by viewing objects, events, and concepts with an objective mind (Lorsbach & Tobin, 1992). The objectivist-based approach is viewed as a bottom-up strategy, where students first learn basic skills. Then, through teacher instruction, they build upon these skills incrementally prior to trying higher ordered tasks (Applefield et al., 2001).

In the objectivist-based classroom, the science teacher views knowledge as discrete blocks of information extracted from external sources, such as books or the Internet, and passes them to students. Each student must first learn these blocks of knowledge before tackling higher-ordered tasks. The objectivist teacher concludes that learning occurs best in a structured and quiet environment, so each student can soak up knowledge individually. The objectivist teacher passes on knowledge through lectures, handouts, and assigned readings with students being assessed through an exam that tests

the acquisition of knowledge (Carson, 2005). In the teaching laboratory, students work individually to perform an experiment in a lab manual that received repetitious prior testing (Tobin, 1993).

Much empirical evidence exists that confirms the teacher-directed approach utilized in the objectivist classroom works (Carson, 2006). The teacher-student role in this situation is frequently what students expect when entering a class (Lapadat, 2000). In addition, the objectivist classroom is easier to manage in most situations (Carson, 2005). For instance, planning and implementing lectures or using detailed lab manuals is an approach that the teacher probably experienced as a learner. Students are comfortable with this customary teaching style, partly because of past experience and partly because the student role is somewhat submissive. On the whole, more information can be covered in the objectivist classroom because time-consuming exercises employed in other classrooms might not take place (Tobin, 1993).

Constructivism

While there are many proponents of objectivism, a mounting movement to have this approach permanently replaced with constructivism as a model in the science classroom and laboratory started two decades ago (Brooks & Brooks, 1999). Proponents of constructivism view knowledge as being internally constructed by the learner through his or her senses and experiences. The student must struggle to decipher the messages received because the learning process is truly messy and challenging (Tobin, 1993). Instead of being a bottom-up approach, constructivist-based teaching is a top-down view

where students are first confronted with complex tasks, and with the aid of the teacher, learn the relevant skills needed to accomplish their objectives (Applefield et al., 2001).

In the constructivist-based classroom, students are expected to interact frequently among themselves, and students work in groups negotiating meaning (Wittig, 1992). Three types of group learning include cooperative learning where students divide tasks, collaborative learning meaning students work on the same task, and tutored learning consisting of a more experienced learner helping others (Roth, 1992). The role of the science teacher who employs constructivism is to guide the learning process through a two-step process, an exploratory phase followed by a discovery phase, and the teacher must refrain from perceiving knowledge as words in books (Flynn, Mesibov, Vermette, & Smith, 2004). The exploratory phase involves students discussing what they know and how they can apply their previous knowledge to a complex task presented by the teacher. The discovery phase focuses on completing the task and learning relevant skills needed to determine outcomes (Matthews, 2003). In the teaching laboratory, students are challenged to design their own experiments in the discovery phase. The constructivist-based classroom does not employ testing to evaluate learning and knowledge but uses additional project-based assignments.

The constructivist-based approach may have many benefits, including more meaningful learning, if students are challenged to associate previous knowledge and experiences with new ones (Tobin, 1993). The exploratory and discovery phases are examples of making learning meaningful through activities that require the acquisition of relevant skills (Bevevino et al., 1999). In addition, constructivist proponents maintain that these phases are ideal for science because the activities emphasize learning of science

through hypothesis testing (Cobb, 1999). The potential for group work to heighten learning through negotiating meaning is another strength.

Another positive attribute is the incorporation of technology, when appropriate, to support learning in the science classroom because it reinforces several tenets of constructivism: (a) learner-centered approach, (b) group work, and (c) real-world situations (Tan et al., 2005). The constructivist teacher focuses learning on students by adjusting instruction to their needs and experiences and by accessing extensive libraries of teaching examples. When properly planned, technology can help students communicate with each other and negotiate meanings in groups. Technology also helps students apply strategies, such as the scientific method, and serves as an organizational tool and a conduit for seeking answers using search engines (Sherman & Kurshan, 2005).

An application for constructivism important in the science classroom is directed study where an instructor acts as a guide and leads students to develop and implement a research project, in a learning environment similar to tutored learning. The directed study uses the exploratory and discovery phase to develop a research design and collect and analyze data. During the exploratory phase, instructors can question students on their interests and previous knowledge, then guide students in creating a project and require modifications until potential problems are resolved. Students engage in discovery as they collect data, perform statistical analyses, and evaluate outcomes with teacher supervision. Manuscript preparation and proposals for additional research are the usual assessment tools beyond oral communication (Tobin, 1993).

Limitations of Objectivism and Constructivism

Although there are many perceived benefits for teachers, there are some limitations to using objectivism as a referent for teaching. Many constructivist proponents discredit the empirical evidence supporting objectivism maintaining that it is based on the biggest fallacy of education, content recitation and regurgitation illustrates content comprehension and application (Lord, 1998). Constructivist proponents claim that students taught in an objectivist-based approach are responsible for learning so much material they often resort to rote memorization, the opposite of meaningful learning, and as such, have little experience with applying their knowledge (Tobin, 1993).

Also, opponents of objectivism in the science classroom maintain that students often construct meaning different from the intention of the teacher. These opponents reason that the students mis-learn information because they are not trying to connect new knowledge provided by the teacher with existing knowledge (Tobin, 1993). In summary, constructivists assert that the objectivist teaching strategy is encapsulated in the belief that students memorize facts presented by the teacher and discovered only by scientists (Lapadat, 2000).

Although proponents of the constructivist-based approach suggest it has the potential to revolutionize science education, even they admit there are inherent disadvantages (Tobin, 1993). For instance, students and teachers unfamiliar with this teaching style may become frustrated and overwhelmed. Both may be too accustomed to the structured environment of lectures and tests that they are not open to hands-on and open-ended experiences and projects. Currently, beginning teachers hesitate to incorporate constructivist-based principles in instruction because of little practice and

knowledge (Teets & Starnes, 1996). Also, students may not be comfortable with working in groups. The instructor must have in place safeguards, such as group member accountability, to ensure that all members are participating. This style does not enable a teacher to present information at a rapid pace, but it has the potential of providing more in-depth learning about fewer topics. Teacher readiness, curricular modifications, and societal acceptance are necessary before constructivism can be tested as a revolutionary panacea for science education (Elkind, 2004).

Root Background Knowledge

Formulation of a model of how to bring current scientific research into the teaching laboratory depends, first, on investigating existing and potential laboratory projects, and second, on selecting a prominent instructional design plan such as the ADDIE Model for modification and classroom implementation. In addition, creation of an actual product and the logical steps taken is important in conceptualizing a model, that others might follow who wish to introduce current research in the classroom. After selecting root competition as the scientific research topic of interest, a fascinating series of laboratory studies followed by instructional design plans and classroom implementation are the elements from which the proposed model are extracted. Such an endeavor requires adequate scientific knowledge about roots including (a) root systems, (b) root development, (c) root functions, (d) root-shoot relationships, (e) root competition, and (f) the split-root technique.

Root Systems

When a seed germinates, the embryonic root named the radicle is the first plant

organ to emerge. Carbohydrates stored in the cotyledon and endosperm provide the

necessary energy for growth and with some plants, such as corn, the radicle elongates as

quickly as 11 cm/day (Kaeriyma & Yamazaki, 1983). However, the fate of this radicle

depends on whether the root is part of a taproot or fibrous root system (Figure 9). In the

taproot system, the radicle becomes the primary root or dominant root that grows

downwards, the ultimate source of all root branches (Feldman, 1988). The taproot system

is predominantly found in gymnosperms and dicotyledonous plants. If a taproot is

injured, such as during transplant, one or more lateral roots can undertake its role

(Weaver, 1926). In some plants, such as the carrot, the fleshy taproot is modified for food

storage through accumulation of high concentrations of sugar, subsequently stored as

starch (Korolev, Tomos, & Farrar, 2000; Raven, Evert, & Eicchorn, 1999).
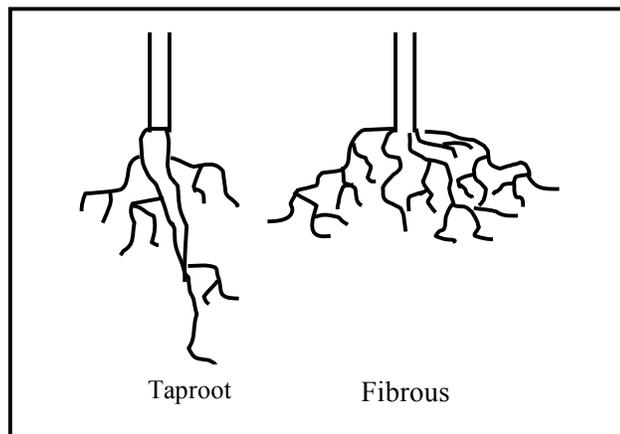
Taproot   Fibrous

Figure 9. Two roots systems, taproot and fibrous.

The fibrous root system is common among monocotyledonous plants. The

existence of the primary root is short-lived in as much as the base of the stem forms many

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root branches, known as adventitious roots because they develop on an organ other than the root (Cannon, 1949). Unlike in the taproot system, there is not a single discernable dominant root but a much branched root ball (Cannon).

Each root system has inherent advantages for the plant. The taproot usually penetrates deep into the soil, thereby, maximizing support of the plant through robust anchorage, and as in the case of the carrot, provides needed storage (Weaver, 1958). The many similar sized roots within the top soil layer of the fibrous root system have a tendency to cling to soil particles, thus preventing erosion of the soil and providing maximum surface area, advantageous for optimum water and mineral absorption (Weaver).

Root Development

Whether it is part of a taproot or fibrous system, each main root and branch root have four developmental zones with graduated transitions: (a) root cap, (b) zone of cell division, (c) zone of cell elongation, and (d) zone of cell maturation (Figure 10). The root cap protects the root growing tip and apical meristem from soil abrasion as it lengthens and pushes past sharp soil particles. Root cap initials, immature cells formed by the apical meristem and destined to become functional root cap cells, undergo cell division to form files of cells that are pushed forward. These cells develop dense starch grains and are capable of detecting gravity as well as produce a slime-like substance called mucigel (Greaves & Darbyshire, 1972). As the cells are pushed closer to the edge of the cap, a predictable pattern occurs: starch grains are digested and copious amounts of mucigel are secreted by exoctyosis (Mauseth, 2003). Mucigel not only protects the root from

desiccation but also lubricates the root surface (Greaves & Darbyshire). Eventually, the

root cap cells are sloughed as soil abrasion destroys their integrity. This pattern of cell

formation in the root cap followed by sloughing usually occurs within four to nine days

(Moore, Clark, & Vodopich, 1998.).
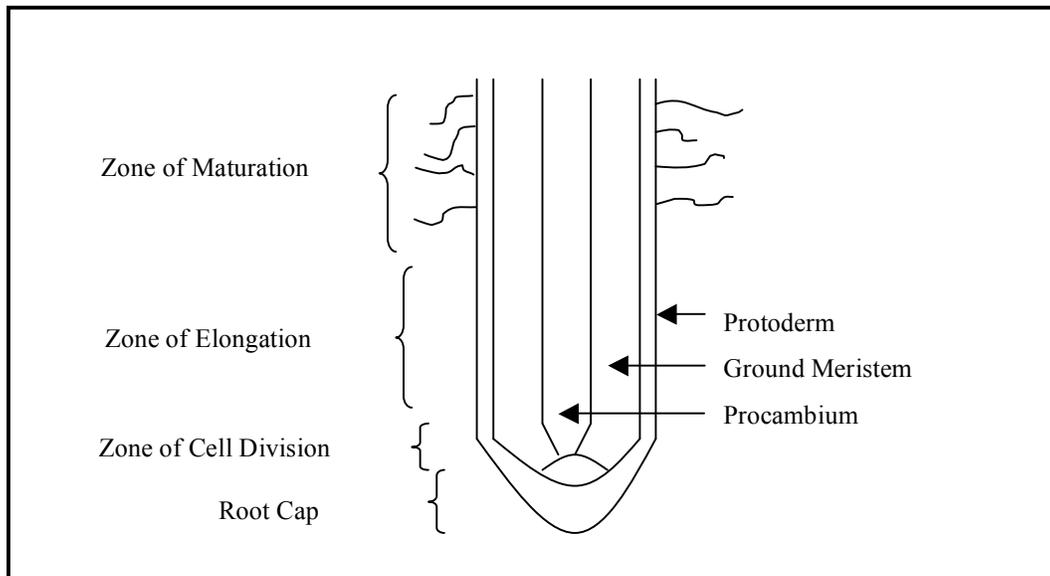
Figure 10. Longitudinal section of a root with labeled developmental zones and meristems.

In the zone of cell division, certain cells, known as the apical meristem, are rapidly

dividing just beyond the root cap to increase the length of the primary root, while other

cells, called quiescent cells, are slowly dividing and acting as a reserve of healthy cells

(Clowes, 1956; Clowes 1975). Cells of the quiescent center are more resistant to harmful

agents, such as toxic chemicals and radiation, than other cells of the root (Clowes, 1961).

For instance, when exposed to intense x-rays, cells of the apical meristem stop dividing;

however, quiescent cells are stimulated to divide and produce a new apical meristem

(Clowes, 1959). Quiescent center cells are also capable of developing a new root apical

meristem, such as when the root cap of corn is surgically excised (Feldman, 1976).

In the zone of cell elongation, which is only a few millimeters in length, cells are

rapidly elongating, but little other activity is occurring (Schieffelbein & Benfey, 1991).

Although none of the cells in this zone are mature, a visible pattern is developing: the

outermost cells are designated protoderm that will differentiate into epidermal cells,

middle cells are the ground meristem tissue that will differentiate into mainly parenchyma

cells, and center cells are provascular tissue (procambium) that will develop into primary

xylem and primary phloem (Mauseth, 2003). Little absorption of water and minerals

occurs in this zone; however, what is absorbed is used directly for root growth

(Mauseth).

In the zone of maturation, several essential processes are occurring, and this zone

is the only region where root hairs are found. Root hairs, which are finger-like extensions

of epidermal cells, greatly increase the surface area for absorption of water and minerals

from the soil solution (Peterson & Farquhar, 1996; Rosene, 1943). For example, it is

estimated that more than 10^{10} root hairs are present on a mature winter rye plant (Dittmer,

1937). Certain epidermal cells, called trichoblasts, form root hairs and are found between

one or more files of atrichoblast cells, non-root hair-forming epidermal cells. Prior to the

formation of root hairs, trichoblasts appear more cytoplasmically dense and shorter

compared to their atrichoblast counterparts (Howell, 1998). The formation of a

trichoblast or an atrichoblast cell is dictated by position (Guimil & Dunand, 2006).

Unlike an atrichoblast cell, a trichoblast cell lies over the anticlinal cell walls of cortical

cell files. At the anticlinal cell walls, localized ethylene production occurs that may be key in the formation of root hairs. Studies show that trichoblasts do not form root hairs when exposed to ethylene inhibitors, and mutants, such as *Arabidopsis constitutive ethylene response1*, constitutively respond to ethylene and create root hairs from all epidermal cells (Tanimoto, Roberts, & Dolan, 1995).

Also found in the zone of maturation are lateral roots that proceed through eight developmental stages categorized by anatomical characteristics and cell divisions (Malamy & Benfey, 1997). A general overview of the process begins with the dedifferentiation of pericycle cells leading to ordered cell divisions that generate a lateral root primordium. As the lateral root develops, it pushes primary root cells aside and emerges as a miniature primary root. Upon completion of its development, the lateral root is functionally and structurally similar to a primary root and its root apical meristem (Malamy & Benfey).

The hormone, auxin, is probably required for lateral root formation since applications of auxin induce lateral root formation (Howell, 1998). However, in tissue culture, there is a stage where root development can occur independent of auxin (Laskowski, Williams, Nusbaum, & Sussex, 1995). Auxin may be required for the formation of the root primordium but is not needed once the meristem is organized. Also important is an A-type cyclin (*cyc1At*) that activates cell division protein kinases at the lateral root site (Ferreira, Hemerly, de Almeida-Engler, Van Montagu, Engler, & Inze, 1994).

Within the vascular tissues in the zone of maturation, the xylem and phloem are fully differentiated and functional. Unlike the shoot, xylem and phloem are not found

within bundles; instead, xylem is at the center of the root surrounded by strands of phloem (Clowes, 1961). Once water and minerals are loaded into the xylem, they are transported vertically through the plant; however, the phloem transports food bidirectionally as sucrose.

Even though root development seems to involve a highly structured process as witnessed by the zones of development, the root is capable of reorganization. For example, when common bean (*Phaseolus*) root tips are surgically split vertically down the middle, each side is able to reorganize and produce a new root. If the root is split into two unequal parts, the new, reorganized roots also become asymmetrical (Howell, 1998; Pellegrini, 1957). In another example, quiescent center cells in the root tips of *Arabidopsis* are ablated using laser microbeam irradiation; these cells are soon replaced by adjacent vascular parenchyma cells that lose their vascular identity and become new, structural and functional quiescent center cells (Van den Berg, Willemsen, Hage, Weisbeek, & Scheres, 1995).

Root Functions

Mature roots participate in five main functions: (a) anchorage, (b) hormone production, (c) water and mineral absorption, (d) water and mineral conduction, and (e) water, mineral, and food storage (Table 3). When plants are properly anchored by their roots, the other organs such as leaves, flowers, and fruits are appropriately oriented to the sun, pollinators, and fruit distributors, respectively (Schieffelbein & Benfey, 1991). In meristematic tissue, roots actively produce hormones such as auxin, cytokinin, abscisic acid, and gibberellin and transport them through the xylem to the shoots to regulate many

aspects of above-ground growth, for instance, to control the size of the shoots so that

transpiration by leaves does not exceed water absorption rate at the roots. Requirement

for hormones produced by the root illustrates the dependent growth relationship with

shoots (leaf and stem). In addition to hormones, roots produce secondary metabolites that

are exported to the shoots, for example, nicotine transported to tobacco leaves (Flores,

Vivanco, & Loyola-Vargas, 1999).

Table 3

Root Functions and Descriptions

Function	Descriptions
Anchorage	Anchor and orient the plant above-ground.
Hormone production	Hormones exported to the shoots to regulate growth.
Absorption	Absorb water and minerals from the soil solution.
Conduction	Transport water and minerals through the xylem to the shoots.
Storage	Store water, minerals, and food for future use.

Roots absorb water and minerals from the soil mostly through their root hairs that

have thin cell walls and a large surface area, plus a mechanism for selectively absorbing

and excluding nutrients. Although microscopic in size, root hairs tremendously increase

surface area of the root systems, for instance, root hairs on a 4-month-old rye plant add

600 m^2 of surface area (Moore et al., 1998).

Certain minerals termed essential elements are required for normal plant growth

and development, including synthesis of molecules and completion of the life cycle

(Mengel & Kirkby, 2001). These essential elements are classified as either macronutrients or micronutrients depending on whether they are needed in large or small quantity, respectively. Examples of macronutrients are carbon, hydrogen, nitrogen, oxygen, potassium, and phosphorus, while copper, zinc, iron, and nickel are required micronutrients (Table 4). In nature, nutrients are absorbed from the soil solution, but in the laboratory, plants are sometimes grown in soil-less or liquid culture, a plant culture method referred to as hydroponics. Nutrient solutions, such as Hoagland's medium, contain all the needed essential elements for plants in the required concentrations (Hoagland & Arnon, 1950). Consequently, Hoagland's medium and liquid culture are utilized in research projects designed to determine nutrient requirements. Hydroponically grown plants require root aeration because roots are dependent upon oxygen for aerobic respiration **(**Jones, 1997).

Table 4

Micronutrients and Macronutrients

Micronutrients	Available for Plants	Macronutrients	Available for Plants
Boron	H_3BO_3	Calcium	Ca^{2+}
Chlorine	Cl^-	Carbon	CO_2
Copper	Cu^+, Cu^{2+}	Hydrogen	H_2O
Iron	Fe^{3+}, Fe^{2+}	Magnesium	Mg^{2+}
Manganese	Mn^{2+}	Nitrogen	NO_3^-, NH_4^+
Molybdenum	MoO_4^{2-}	Oxygen	O_2, H_2O, CO_2
Nickel	Ni^{2+}	Phosphorus	$H_2PO_4^-, HPO_4^{2-}$
Zinc	Zn^{2+}	Potassium	K^+
		Sulfur	SO_4^{2-}

Note. Based on Moore, R., Clark, W. D., & Vodopich, D. S. (1998). *Botany* (2nd ed.). New York: McGraw Hill.

Minerals, usually available in ion form (Table 4), are taken up at the root hair through passive and active mechanisms. Passive mechanisms include diffusion, facilitated diffusion, and co-transport. However, more often, minerals are taken up through active transport in which one molecule of adenosine 5'-triphosphate (ATP) per ion is required for uptake against a concentration or electro-chemical gradient (Haynes, 1990). Active transport enables the plant to concentrate and store ions in higher concentration in roots than found in the outside environment. Mineral uptake rarely occurs through endocytosis because the outward turgor pressure of the vacoule prevents the requisite infolding of the plasma membrane (Haynes).

Minerals taken up by the roots through active transport are cations and anions, which are most available to the plant when dissolved in the soil solution. Cations, such as K^+, Ca^{2+}, Mg^{2+}, and Cu^{2+}, are attracted to the negatively charged soil particles in the form of clay micelles; however, the bonding is weak enough that bound cations can be exchanged for other cations from the soil solution before being absorbed by the root. The Carbonic Acid Exchange Theory explains how cations associated with anionic clay or soil particles become available to roots (Buscher, Koedam, & van Speybroeck, 1990). Roots and root hairs give off carbon dioxide as a product of aerobic respiration. Some of the carbon dioxide dissolves in the soil solution and reacts with water to form carbonic acid capable of dissociating to a proton and a bicarbonate ion. Bicarbonate, in turn, dissociates to release a second proton and carbonate ion (Figure 11). As the protons increase in concentration in the soil solution, equilibrium kinetics favor replacement of cations attached to anionic soil particles with protons; thus, the bound cations enter the soil solution and are available for root uptake (Buscher, et al.).

$$CO_2 \text{ (carbon dioxide)} + H_2O \text{ (water)} \rightarrow H_2CO_3 \text{ (carbonic acid)}$$

$$H_2CO_3 \text{ (carbonic acid)} \rightarrow H^+ \text{ (proton)} + HCO_3^- \text{ (bicarbonate anion)}$$

$$H^+ + HCO_3^- \text{ (bicarbonate anion)} \rightarrow H^+ + H^+ + CO_3^{2-} \text{ (carbonate anion)}$$
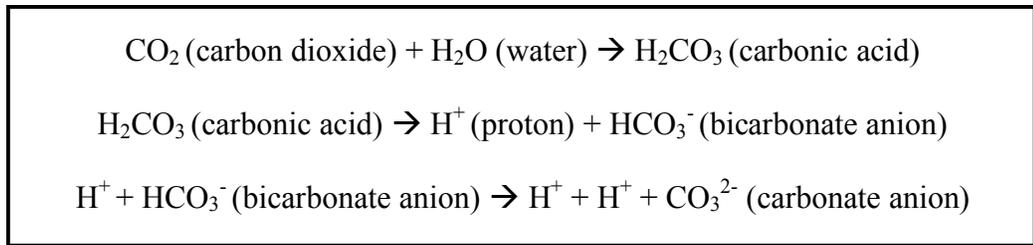
Figure 11. Formation of carbonic acid when carbon dioxide released by the root dissolves in soil water and the subsequent dissociation of carbonic acid to release protons for cation exchange.

Other factors that release protons into the soil solution, such as secretion of acids by bacteria, decomposition of humus, and acid rain, also cause the freeing of cations from

the clay micelles (Barbour, Burk, Pitts, Gilliam, & Schwartz, 1999). Therefore, the soil pH, which is the concentration of free protons in the soil solution, greatly impacts cation exchange and the retention of cations. Lower pH corresponds to more protons in the soil solution meaning that more cations are released from clay particles and absorbed by roots, or alternatively, are washed downward in the soil by percolation. Soils high in free protons are often nutrient poor because cations are rapidly lost into ground water. On the other hand, higher pH means that few protons are available for cation exchange; thus, cations are adhered to soil particles and are not very available for root uptake (Barber, 1984).

Soil pH also affects the solubility of minerals. Aluminum and manganese are so soluble in acidic soils that they can reach toxic levels, while in alkaline soils iron, copper, and zinc are nearly insoluble, and thus, unavailable to plants (Barber, 1984). A slightly acidic pH of 6.5 to 7.0 is preferred by plants because many elements including iron, zinc, and phosphorus are highly soluble (Barbour et al., 1999). However, natural selection has favored mutations that allow specific plants to tolerate and even thrive in extreme soil pH. For example, desert plants live in alkaline soils, while wetlands plants thrive at low soil pH (Barber).

Roots can directly alter soil pH through soil acidification with protons directly secreted into the immediate environment. Often this is in response to a mineral deficiency, for instance, an iron deficiency. Iron is largely found as a ferric ion (Fe^{3+}) in the soil solution but is highly insoluble at neutral or alkaline pH. While soil acidification is one method to increase iron solubility, two other mechanisms are employed by roots, reduction of ferric to ferrous iron (Fe^{2+}) and chelation of the ferric iron (Taiz & Zeiger,

1998). An enzyme found in the plasma membrane of roots, called iron-chelating reductase, changes ferric iron to its more soluble form, ferrous iron, at the surface of root. Iron-reducing enzyme activity is amplified when soil-iron is low, and the resulting soluble, ferrous iron is taken up by the root (Volker & Wolf-Gladrow, 1999).

The second mechanism involves roots exuding organic acids, such as malic acid, citric acid, and piscidia, that chelate iron. These exudates form a pincer-shaped molecule that weakly holds iron between the tines, thus, giving iron the solubility characteristics of the chelator. Other iron chelators that form highly stable complexes with the ferric ion include phytosiderophores, a class of compounds that are composed of amino acids such as mugineic acid (Taiz & Zeiger, 1998). Phytosiderophores and iron complexes are taken up as a whole unit by the root (Volker & Wolf-Gladrow, 1999).

Unlike cations, anions are attracted to cationic soil particles, which are present in limited numbers. Consequently, anions such as SO_4^{2-} and NO^{3-} are rapidly leached from the soil solution, and their absence frequently limits the growth of plants (Barbour et al., 1999). Contrary to expectations, the anion, phosphate, is retained in soil because it forms insoluble precipitates with compounds composed of iron, aluminum, or calcium (Gilroy & Jones, 2000). Just as with cations, these precipitates are unavailable to plants for uptake and must be returned to a soluble form for absorption and transport by xylem.

To replenish essential nutrients leached by rainfall into deeper soil layers inaccessible to roots, fertilizers are often needed. In the case of nitrogen, most fertilizers provide it as the cation, ammonium (NH_3^+). However, this cation does not often bind to the clay micelle because bacteria frequently and quickly convert it to nitrate (NO_3^-), an anion, through a process called nitrification (Hooper, Vannelli, Bergmann, & Arciero,

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1997). These nitrifying bacteria also convert ammonium produced by nitrogen-fixing

bacteria and from decaying organic matter to nitrate. Even though the roots are able to

absorb this anion, nitrate must be reduced to ammonium by enzymes (nitrate reductase

system) within the plant to be incorporated into amino acids and other organic

compounds (Hooper et al.). A parallel situation exists for sulfur; it is absorbed as sulfate

(SO_4^{-2}), but must be reduced to sulfide (S^{2-}) within plant cells before being incorporated

into proteins (Leustek & Saito, 1999).

Water absorbed by the root is available in small capillaries formed by loosely

packed soil particles. Water enters the root through a passive mechanism, called osmosis,

and moves from a higher concentration to a lower concentration across cell membranes.

The high solute concentration of minerals absorbed by active transport influences water

concentration and movement, creating a lower concentration of water inside the root as

compared to the soil. Consequently, raised solute concentration hastens the rate of

osmosis and water uptake (Barbour et al., 1999).

Once water and minerals are absorbed by the roots, the next step is lateral

transport to the xylem. Since water and minerals are being absorbed at the root hairs in

the lower portion of the zone of maturation, a cross section of the root includes the outer

epidermal region internally bounded by a huge area composed of parenchyma, a tissue

that stores food, water, and minerals. Abutting the parenchymatous cortex is the

endodermis, a cylinder of tightly packed cells with an outer ribbon of wall known as the

Casparian strip impregnated with lignin and suberin (DuPont & Leonard, 1977). At the

center of the root cross section are the vascular tissues, xylem and phloem, responsible

for vertical movement of water and minerals as well as sugar, respectively (Figure 12).
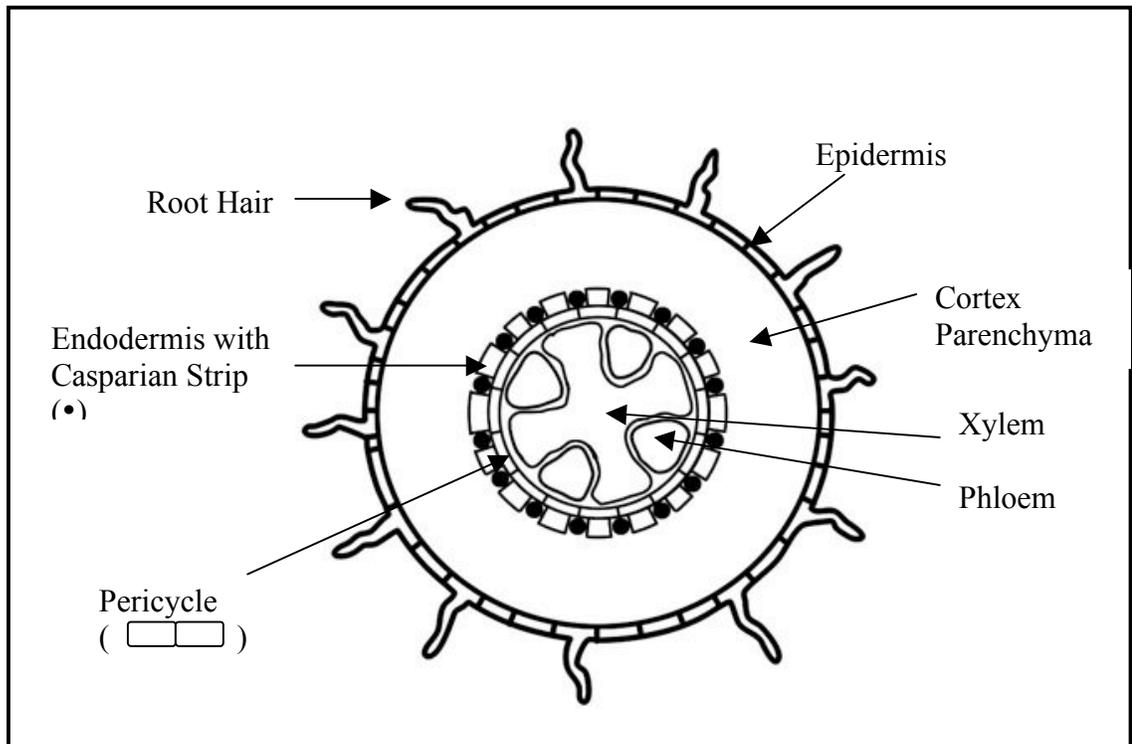
Figure 12. Cross section of a dicot root through a very young region within the zone of maturation.

Water and minerals entering through the root hairs take either a biotic or abiotic path to the xylem. In the biotic or living path, hydrophilic substances including polar molecules, move through the living parts of the cells, such as the plasma membrane and cytoplasm. On the other hand, movement through the abiotic or non-living regions of the root include the cell wall and intercellular space. Once the water and minerals reach the endodermis, substances must move biotically because the intercellular space on four sides of the endodermal cell are rendered hydrophobic and impassable by the Casparian strip. Thus, the selectively permeable plasma membrane of endodermal cells regulates which substances reach the xylem for vertical transport (DuPont & Leonard, 1977). While suberin blocks the intercellular space of young endodermal cells, continuous addition of

suberin to the cell wall during the aging process renders older endodermal cells impervious to water and minerals. Continual suberin addition is why water and minerals are rarely absorbed 5 cm above the root tip (Moore et al., 1998).

Once water and minerals move through the endodermis, they reach the xylem and are conducted vertically. Constant removal because of vertical transport in the xylem maintains the lateral gradient; thus, water and minerals are in highest concentration at the root hairs and lowest at the xylem. How conduction, that is, the vertical movement of water and minerals in the xylem, operates is best explained by the Cohesion Tension Theory or Transpiration Pull Theory (Levitt, 1956; Hungate, 1934; Thut, 1932), different titles for the same theory. A number of factors work in concert. Xylem anatomy contributes fine capillaries as the cell types tracheid and vessel element that are hollow, dead cells with extremely strong cell walls because of high concentrations of lignin. The cellular capillaries keep their shape under pressure, forming interconnected fine tubes full of water extending from the root to the leaf. This continuous column of water exerts a tensile strength caused by the cohesive forces of water molecules and enables water to move upward in the tallest trees, redwoods (*Sequoia sempervirens*) over 110 m (Koch, Sillett, Jennings, & Davis, 2004).

Transpiration, loss of water as a vapor at the leaf through pores called stomates, applies a pull on the continuous column of water elicited when water molecules change from liquid to gaseous state (Taiz & Zeiger, 1998). The water-potential gradient caused by the evaporation of a water molecule lifts the water column upward, one water molecule at a time. The cohesion of water molecules prevents the column in the xylem from breaking, while the adhesion of water molecules to cell walls of tracheids and vessel

elements prevents gravity from draining the column. If conditions are not right for transpiration, the loss of water as a liquid, known as guttation, can maintain the gradient (Hughes & Brimblecombe, 1994). Besides a water gradient that is highest at the root and lowest at the leaf, there is a nutrient gradient distributed identically to the water gradient. The low end of the nutrient gradient is maintained by nutrient consumption during photosynthesis and growth at the leaf and stem.

In addition to absorbing and conducting water and minerals, roots can also store large amounts of water, minerals, and starch. For example, biennials, such as carrots, concentrate their reserves in a main taproot during the first winter. If carrots are not harvested after their first year, the plant uses its stored water, minerals, and starch for vegetative and reproductive growth during the second growing season. For a woody dicot, the reserves are stored in the roots during the winter, and when spring arrives, the starch is converted to sucrose and transported to the newly growing leaves and branches as a source of energy and the skeletal structure of new molecules (Sauter & van Cleve, 1994).

Root-Shoot Relationship

An analysis of root systems, development, and function cannot be complete unless the inter-relationship between roots and shoots also is taken into account (Ericsson, 1995). One obvious way in which they are related is roots absorb the water and minerals conducted through the xylem and consumed at the shoots. In addition, the root and shoot relationship is often described in terms of source and sink. The shoots are the source of photosynthate exported as sucrose to the roots that act as a sink either storing or

consuming the food. In spring, the roles are reversed for perennials when stored food in the root becomes the source for fueling regrowth at the shoot, the sink. Ultimately, the roots are wholly dependent on the photosynthetic shoots for organic nutrition and normal development (Taiz & Zeiger, 1998).

However, the relationship between roots and shoots is considerably more complex than sink and source because the coordination of their growth depends on hormonal substances contributed by both (Russell, 1977). For example, cytokinins are primarily produced in the roots and transported to the shoots through the xylem to promote cell division and vascular tissue and shoot development. Auxins, produced in the shoot meristematic tissue, are transported to the roots through the phloem and promote root development (Russell).

The coordination of growth between the roots and shoots is especially evident in an environment that is constant (Figure 13). A logarithmic, linear relationship is often seen between the dry weights of roots and shoots (Russell, 1977; Pearsall, 1927). For example, in the case of peas (*Pisum spp.*), the logarithmic stem weight is equivalent to logarithmic root weight under constant conditions; however, this characteristic is mutable (Russell). In other words, while a relationship may be found for many plants during their vegetative stage, changes can occur during the transition to reproduction. Many cereals, including oats, continue to increase shoot mass but decrease root mass in their reproductive stage, thus altering the linear relationship seen in the vegetative stage (Russell).
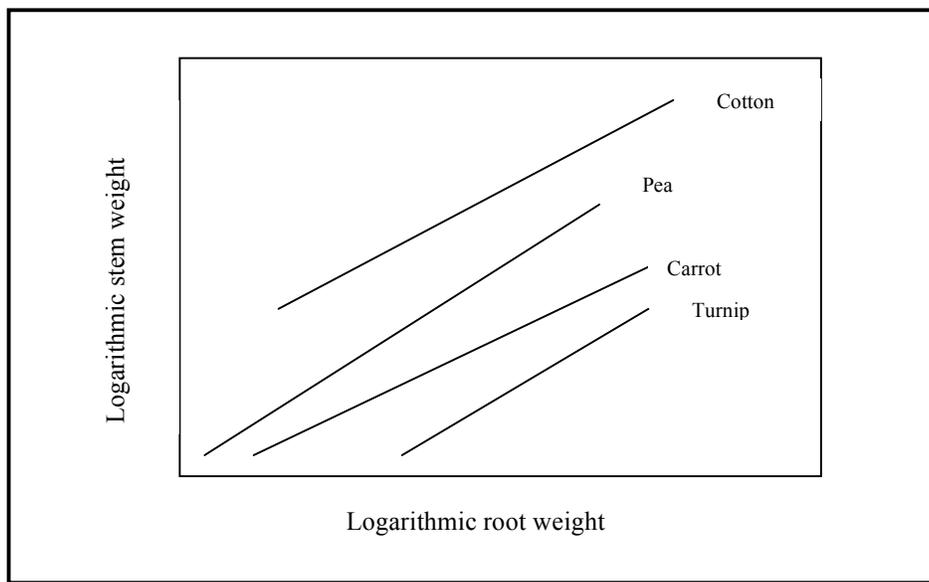
Figure 13. Logarithmic relationship of root-shoot mass for several crop plants in the vegetative stage.

Changes in environmental factors also may lead to a change in the logarithmic, linear relationship between root and shoot mass. Light intensity, nutrient supply, and temperature are major variables that influence the dry weight ratio between roots and shoots (Russell, 1977). For instance, root and shoot production is often less in an environment with low light intensity; however, between the two, the root weight seems to be more negatively affected (Ericsson, 1995). In terms of nutrients, a plant that experiences greater growth with the addition of an external supply of nitrogen usually increases shoot growth more than root growth. While many experiments endeavor to discover relationships between varying levels of nutrients or other environmental factors and root-shoot mass, the major conclusion found is that "no simple generalization can apply to such situations" (Russell, p. 21).

While changes in light intensity are principally experienced by the shoots and

varying nutrient concentration initially affects absorption at the roots, changes in temperature directly affect both roots and shoots simultaneously. For example, when plants experience unfavorable temperatures for an extended period, the greatest effect is on meristematic activity throughout the plant; thus, growth of the roots and shoots are equally retarded (Russell, 1977).

Root Competition

Another important concept is root competition, which occurs when there is a decrease in the resources needed for plant growth and maintenance. Plants that have similar demands for limited resources experience greater competition than those that do not. Generally, competition patterns are assigned to two categories: intra- or inter-plant competition (Barbour et al., 1999). Intra-plant competition focuses on competition among plants of the same species. Although not initially apparent, differences in height, leaf expanse, lateral root formation, and production of fruits and seeds develop as a result of intra-plant competition. Inter-plant competition involves different species competing with greater effects observed for plants having similar body types and growth patterns (Weaver & Clements, 1957). While plant competition is classified based on the species concerned, it is also discussed in terms of specific resources that plants compete for as well as other factors, such as competition for pollinators or seed dispersal agents (Etherington, 1975).

There are five resources that influence plant competition: (a) space, (b) light, (c) carbon dioxide, (d) nutrients, and (e) water. Shoots compete for space, light, and carbon dioxide, while roots compete for space, nutrients, and water (Etherington, 1975). In

keeping with the theme of this project, only root competition will be described in detail. In terms of space, many roots systems are able to utilize different areas of the soil, thus promoting avoidance of competition. Competition of roots for nutrients and water is considered comparable to competition for space, in that, excess space provides excess water and nutrients. Plants capable of producing more dry weight and leaf area with access to limited nutrients and lower amounts of water are better competitors (Barbour et al., 1999).

Among the unusual or external factors that drive root competition is sensitivity to CO_2 concentrations that emanate from root aerobic respiration and cause the CO_2 concentrations to be higher below-ground than above-ground (Etherington, 1975). Because CO_2 in wet soil becomes carbonic acid and affects soil pH, some plant species are capable of outcompeting others when CO_2 levels are high. A second unusual factor contributing to competition is allelopathy, the ability of a plant to produce chemical exudates from living root tissue or decomposing plant residues that deter normal growth in other plants (Kato-Noguchi, 2003). For example, peas produce the allelopathic chemical, pisatin, that inhibits growth of roots and seedlings of other plants, including cress and lettuce. Another allelopathic chemical, β-(3-isoxazolin-5-on2-yl)-alanine (βIA), found in peas reduces root growth in competing species and causes necrosis in the root tips of many grasses (Schenk & Werner, 1991). Alleopathy is under investigation as a possible ecologically friendly weed control strategy; for example, a mulch of killed pea plants decreases weed production (Kato-Noguchi).

Split-Root Technique

The split-root technique, developed over 100 years ago, provides a unique model for investigating different root processes, such as root competition (Bohm, 1979). This procedure involves manipulating root development to form two equal root masses (Figure 14). Once the twin roots are established, they are placed in separate pots and receive various treatments to determine root and shoot response. Originally, this method is primarily employed to test alternate nutrient formulas on root pairs (Bohm), but in the 1990's, renewed interest elucidates other aspects of root competition, and this more recent knowledge base fuels the experimental protocols emulated or newly designed in the current study. Besides investigating twin roots, the removal of half the root mass from a twin-root plant forms a single-root plant useful in designing root competition experiments (Gersani & Sachs, 1992).

Figure 14. A split-root pea plant.

Current Root Competition Literature

Recent scientific experiments utilize the split-root technique to address new concerns about (a) nutrient effects, (b) impact of competitors, (c) root discrimination, and (d) root habitat selection models (Fallik et al., 2003; Maina et al., 2002; Gersani et al., 2001; Gersani et al., 1998; Gersani & Sachs, 1992). The current literature on split-root investigations offers an attractive opportunity to develop a series of educational modules on root development, function, root-shoot relationships, and competition amendable to active student participation in laboratory research.

Nutrient Effects

One important series of experiments is designed to pose questions about root growth in relation to available nutrients (Gersani & Sachs, 1992). A split-root pea plant is grown with twin root masses in two neighboring pots with the shoot balanced on the adjacent pot rims, a plant placement known as a "fence-sitter," that is, the plant is sitting on the fence between two pots (Figure 15). Each root of a fence-sitter is treated with one of the following: 0, 1, 10, or 50% Hoagland's medium (Hoagland & Arnon, 1950). After approximately a month, root mass of the fence-sitters is determined as dry weight. Within each fence-sitter, the two root masses are basically the same weight, however, among the various treatments, as nutrients increased so did root mass. Thus, plants treated with 50% Hoagland's medium have the greatest root mass (Gersani & Sachs).
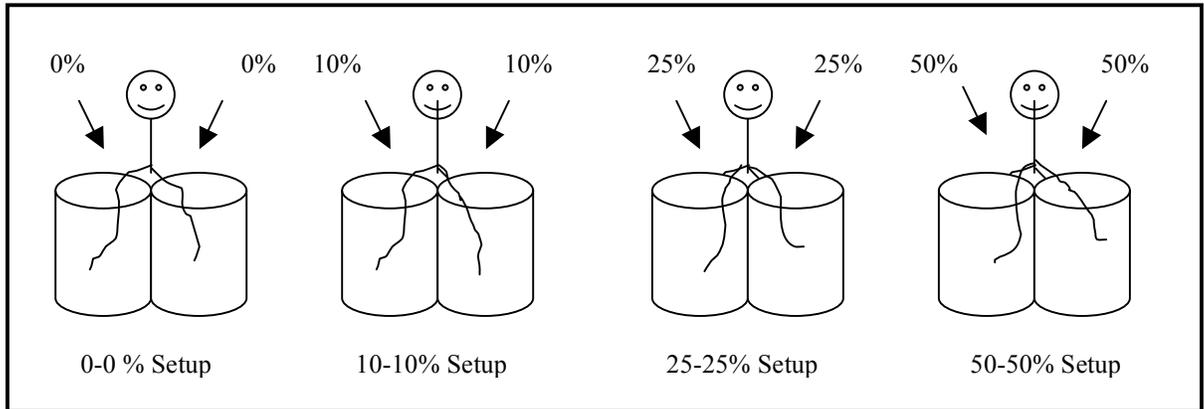
Figure 15. Replicate fence-sitters receive 0, 10, 25, and 50% Hoagland's medium and root mass is compared after 4 weeks.

In other experiments, initial root mass and nutrient concentrations are compared (Gersani & Sachs, 1992). Some trials repeat the fence-sitter scenario, while other plants begin the experiment with only half of the normal root mass, single-root plants (Figure 16). After receiving identical nutrients for several weeks, the final root mass for single-root plants is statistically the same as twin root mass. Apparently, the single-root plant grew so rapidly that it caught up with the twin root plant, suggesting some plants are programmed by nutrient availability to attain a particular root mass.
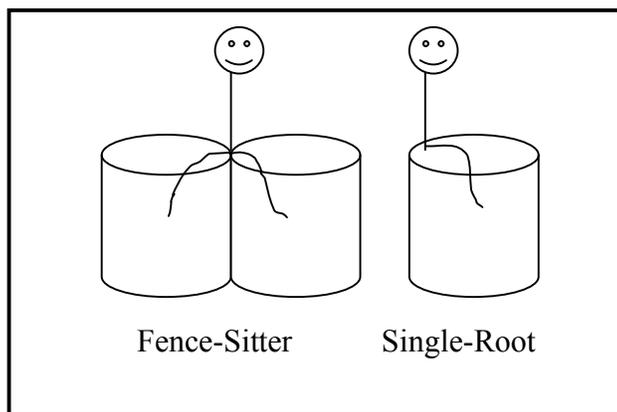
Figure 16. Fence-sitters versus single-root plants.

While previous studies compare single-roots with twin roots receiving identical nutrient regimes, an interesting experiment examines whether twins vary when exposed to different nutrient levels (Gersani & Sachs, 1992). One twin experiences water while the other experiences 50 % Hoagland's medium (Hoagland & Arnon, 1950), or a 0-50% nutrient comparison (Figure 9). Other scenarios tested are as follows: 10-50, 25-50, 50-50, 10-0, and 25-0% (Gersani & Sachs). Results confirm that even root growth in pots with 50% Hoagland's medium is influenced by nutrient conditions faced by the other half of the root system. In the 0-50% comparison, the twin receiving the 50% nutrients has substantial root growth, while the twin with 0% nutrient addition yields little growth. However, in the 25-50% assessment, the growth in the twin with excess nutrients is reduced, and growth in the twin receiving lower nutrients is intermediate. It seems that root growth might reflect both nutrient concentrations in the environment and nutrient conditions experienced by other portions of the root mass.
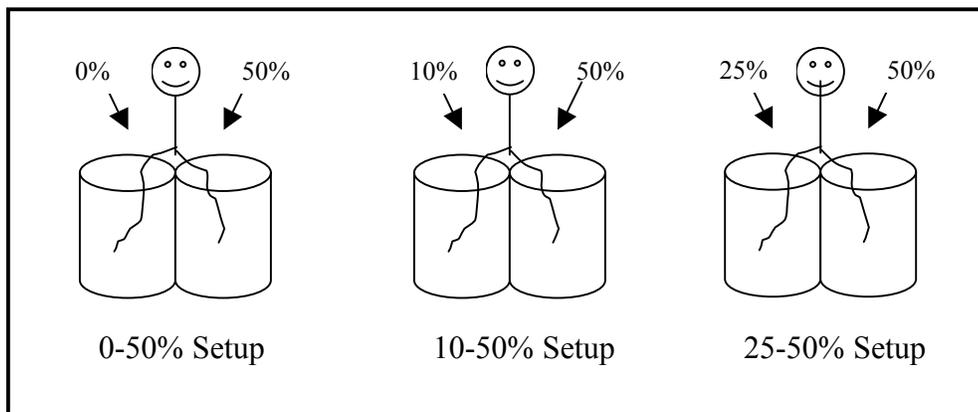
Figure 17. Fence-sitters with twin root masses exposed to different nutrient levels.

Impact of Competitors

The split-root technique is useful for investigation of spatial impact on peas

because twins may be exposed to a number of competitors ranging from zero to five

(Gersani et al., 1998). Some split-root plants test effects on root mass when half of the

root mass has no competitors, and the other half is exposed to multiple competitors

(Figure 18). The greatest root mass is attained in the pots without competitors, while the

number of competitors inversely influences root mass in the twin, i.e., the more

competitors the smaller the root mass. Even though the pots initially receive the same

amount of nutrient, multiple competitors must share resources, and thus, on an individual

basis receive less nutrition. As a consequence, a root mass in a pot with competitors has

less access to nutrients than a root mass without competitors. How these plants allocate

root mass follows the idea that the root mass matches the available nutrients, sometimes

referred to as resource matching.
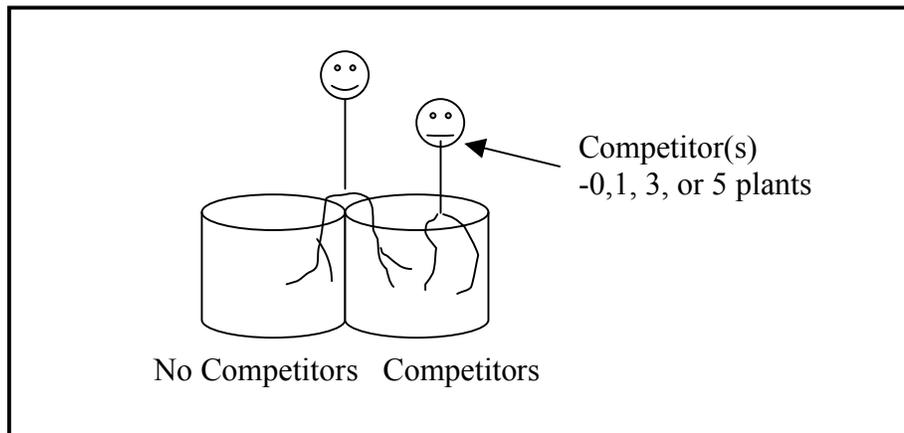
Figure 18. Fence-sitters positioned so only one twin experiences competition.

Root Discrimination

Another question of interest is the mechanism by which a plant discriminates roots from self and another plant (Fallik et al., 2003). In an elaborate experiment, double plants are created, which means experimental plants had both split roots and shoots. Although an innovative design employing intact double plants and separated double plants is used, the factors governing responses of multiple root masses is not conclusively established, but speculation concludes that the mechanism is "at least partly based on physiological coordination among roots" (Fallik et al., p. 531).

Habitat Selection Models

Intra-root versus inter-root competition in Kenyan beans (*Phaseolus varigaris*) is investigated through employing the split-root technique (Maina et al., 2002). In this project, inter-plant competition is defined as competition with a second plant of the same species, not competition between different species, and intra-plant competition refers to competition within one plant. One question centers on determining the habitat preference of competing bean roots. Based on the three most likely plant responses, a predictive model, known as the habitat selection model is formulated. The anticipated responses include (a) inter-plant avoidance, (b) resource matching, or (c) intra-plant avoidance (Table 5). The experimental design for testing habitat preference involves the creation of "fence-sitters" and "owners" (Figure 19). In both situations, two split-root plants and two pots are utilized. In addition, each plant experiences the same total space and nutrient conditions (Maina et al.). In the fence-sitter setup, two split-root plants share two pots, while in the owner scenario, a single split-root plant occupies each pot.
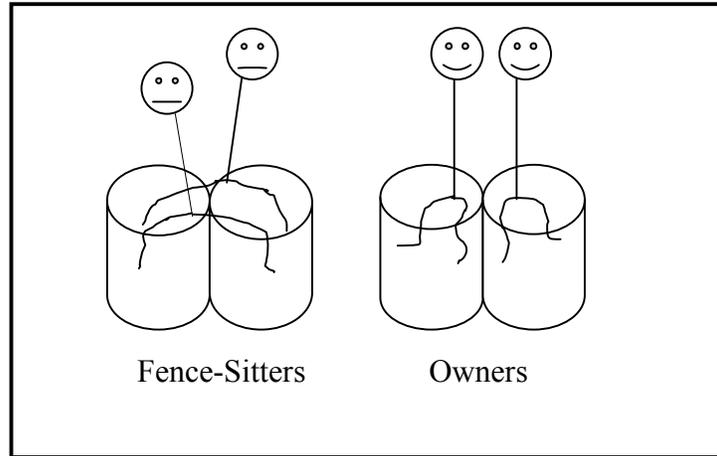
Figure 19. Fence-sitters versus owners and the habitat selection model.

The inter-plant avoidance response presumes that plants try to avoid inter-plant competition (Sachs, Novoplansky, & Cohen, 1993); therefore, plants prefer to proliferate roots only among themselves. Under this assumption, it is expected that each fence-sitter prevents inter-plant competition by segregating its roots so that each plant becomes an owner of one pot, and root production by fence-sitters is less than owners. Conversely, owner roots are expected to flourish because only intra-plant root competition is experienced. Consequently, expected root production in an owner is greater than root production in a fence-sitter (Table 5).

Table 5

Summary of Root Production for Each Habitat Selection Model in the Fence-Sitters Versus Owners Experiment

Response	Root Production
Inter-plant avoidance	Fence-sitter < Owner
Resource matching	Fence-sitter = Owner
Intra-plant avoidance	Fence-sitter > Owner

The resource matching response assumes that root proliferation will match the available resources regardless of space-sharing patterns (Maina et al., 2002; Fretwell & Lucas, 1970). If nutrients are highly accessible, then root production is substantial. If nutrients are limited, then growth is slow and root mass small. In these experiments (Maina et al.), initial nutrient levels and root mass are identical for each pot and only inter- versus intra-plant competition varied. Because the root mass in fence-sitters equals root mass in owners after 4 weeks of growth, it is assumed that the amount of nutrients governs the response and plant responses such as these are identified as resource matching within the habitat selection models (Table 5).

The intra-plant avoidance response, which is based on the game theory model, states that some plants avoid proliferating roots among themselves (Gersani et al., 1998). Under this approach, plants establish roots among neighbors to try to maximize whole-plant fitness. The assumption is that it is better to 'steal' resources from a neighbor than from oneself. However, if plants over produce roots in an attempt to take all the nutrients in the environment, they are engaging in a response called the "tragedy of the commons" (Hardin, 1968). In this response, the collective yield of the plant is sacrificed because of

the energy going into excess root production (Gersani et al., 2001). If plants multiply roots among roots of other individuals, then root mass in a fence-sitter is greater than in an owner (Table 4), and the competition fits the habitat selection model for intra-plant avoidance.

In actual experiments with Kenyan beans, the root mass differs substantially between the fence-sitters and owners after roughly a month. The "fence-sitters produce 150% more root mass per individual than owners," (Maina et al., 2002, p. 235) proving that the intra-plant avoidance model governs the plant response. Additionally, the plants in the owner scenario have significantly higher shoot-to-root ratios than the fence-sitter plants (Maina et al.). Unlike fence-sitters, the owner plants are allocating more energy to shoots than root production. This fence-sitter versus owner experiment represents a simple and elegant design to investigate how a plant might allocate root and shoot mass. While the Kenyan bean seems to "prefer" to proliferate roots among its neighbors as compared to itself, not all plants react in the same fashion (Bazzaz, 1991).

Further investigation of plant response to various types of root competition is an ideal project for the classroom laboratory because fundamental plant biology explained in lecture is investigated experimentally in the laboratory using current research techniques and addressing open-ended, recent research problems. Lecture topics suited to root competition studies include plant nutrition, root anatomy and development, root function and physiology, and competition, and all represent topics commonly taught in advanced, college-level botany courses. Laboratory protocols afford direct experiences with altering root development in forming split-root plants, designing experiments that test root competition, collecting data, performing statistical analyses, and evaluating outcomes.

The stepwise process of modifying research on root competition found in the scientific literature for classroom applications can form the bases upon which to construct a model others might use to add more recent research ideas and methods to the curriculum and as a way to motivate students to become future scientists.

CHAPTER III

METHODS

The methods are broken into 4 parts: (a) instructor design of root competition experiments, (b) plan for instruction, (c) idea for field trials, and (d) strategy for science education model development. The first portion of the study is devoted to the scientific efforts of the instructor, including a broad literature search followed by intense experimentation in the laboratory designed to identify new topics suited for the classroom. Once root competition and split-root assays are identified as the instructional topics, laboratory research efforts are concentrated on identifying a suitable plant species, altering root development to produce twin root masses, adapting and designing experiments and testing hypotheses, and collecting and analyzing data. Efforts then shift to planning how to teach the new module on root competition using the ADDIE Model as a guide. During the implementation phase, a general plan for two small, single trials employing objectivism and constructivism, separately, is devised. The natural progression of scientific inquiry and the crucial components of instructional development are utilized to create a model for selecting and modifying scientific research for the college teaching laboratory.

Identification and Experimental Modification of the Laboratory Project

Prior to canvassing recent scientific literature for the new research/teaching project, a set of criteria is formulated to guide the selection process (see Chapter I). Topics meeting the criteria are carefully analyzed and checked against published Laboratory Manuals to avoid duplication. Once the final topic is identified, methods and protocols are designed that specifically address the project.

An appealing group of journal articles, discussed in the Literature Review, Chapter II, that uses young seedlings modified to form twin root masses, aptly named split-root plants, addresses multiple aspects of root competition (Fallik et al., 2003, Maina et al., 2002; Gersani et al., 2001; Gersani et al., 1998; Gersani & Sachs, 1992) and fits the imposed criteria. The efforts needed to adapt the root competition studies for the classroom are divided into two major tasks: (a) laboratory experiments, and (b) instructional plan.

Laboratory Experiments

The initial laboratory experiments test readily available species for their ability to form split-root plants, germination rate, viability, ease of handling, and suitability for the classroom. Once the test species is selected, two modified experiments based on current scientific literature (Maina et al., 2002; Gersani & Sachs, 1992) and three original experimental designs are assayed for root competition and the habitat selection model that explains the results (Table 5).

Modification of the Split-Root Technique for the Classroom

A reliable plant species and simple protocols for creating a split-root plant are essential to project success. Criteria for species adoption include availability of seed, germination and survival rate of seedlings, high success rate with forming split-root plants, hardiness to rough handling, and relatively short time to maturity. Pea, cucumber, lima bean, tomato, and corn seeds, without anti-fungal coatings, are subjected to the split-root method, a labor intensive procedure (Figure 20, column a), and scored on their ability to meet all adopted criteria (Table 6). Of the species tested, only Sugar Ann English peas (*Pisum sativum var.* Sugar Ann English Peas) met the necessary criteria; thus, all subsequent experiments are designed with peas.

Table 6

Checklist for Scoring Plants on Selection Criteria

Species	Readily Available	Hardy	Days Until Harvest	Forms Split-Roots	Split-Root Efficiency	Split-Root Survival
Pea						
Cucumber						
Lima Bean						
Tomato						
Corn						

Additional trials with Sugar Ann English peas are designed to tailor split-root development to fit classroom needs: student manipulation, weekly classroom schedule, and incubation conditions. Four handling procedures (Figures 20, columns b-e) are designed and implemented. Variations among the procedures are limited to (a) presence

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or absence of seed aeration, (b) timing between germination and severing root tips, (c) incubation of severed-root plants in rolls of wet paper towels (ragdolls) or in vermiculite (inert potting mix), (d) incubation temperature, and (e) incubation time prior to transfer to experimental pots. Each plan is evaluated for successful formation of split-roots, occurrence of major events spaced at weekly intervals, and completion of the life cycle within the shortest time frame.
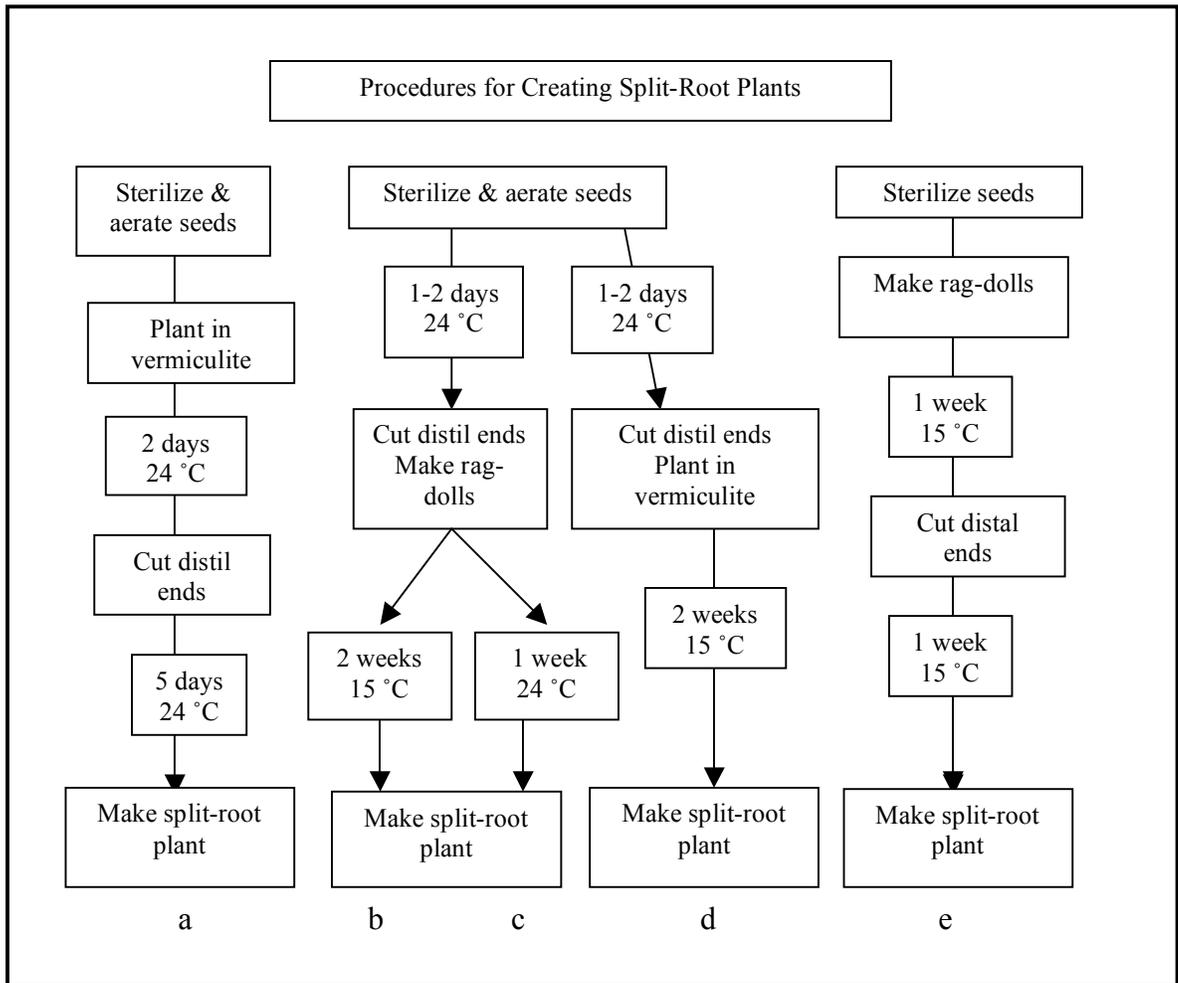
Figure 20. Split-root technique reported in the literature (column a) and four protocols tested for adapting the split-root technique to the classroom (columns b-e).

Based on outcomes from these initial trials, all subsequent experiments use sterilized pea seeds germinated in ragdolls using sterilized paper towels at 15 ˚C for 1 week without aeration (Figures 20, column e & 21). Root tips are severed to cause proliferation of root branches at 1 week, and seedlings are incubated for an additional week at 15 ˚C when root branches are excised leaving two distal branches of nearly equal size. Plants are ready for classroom experiments in 2 weeks.
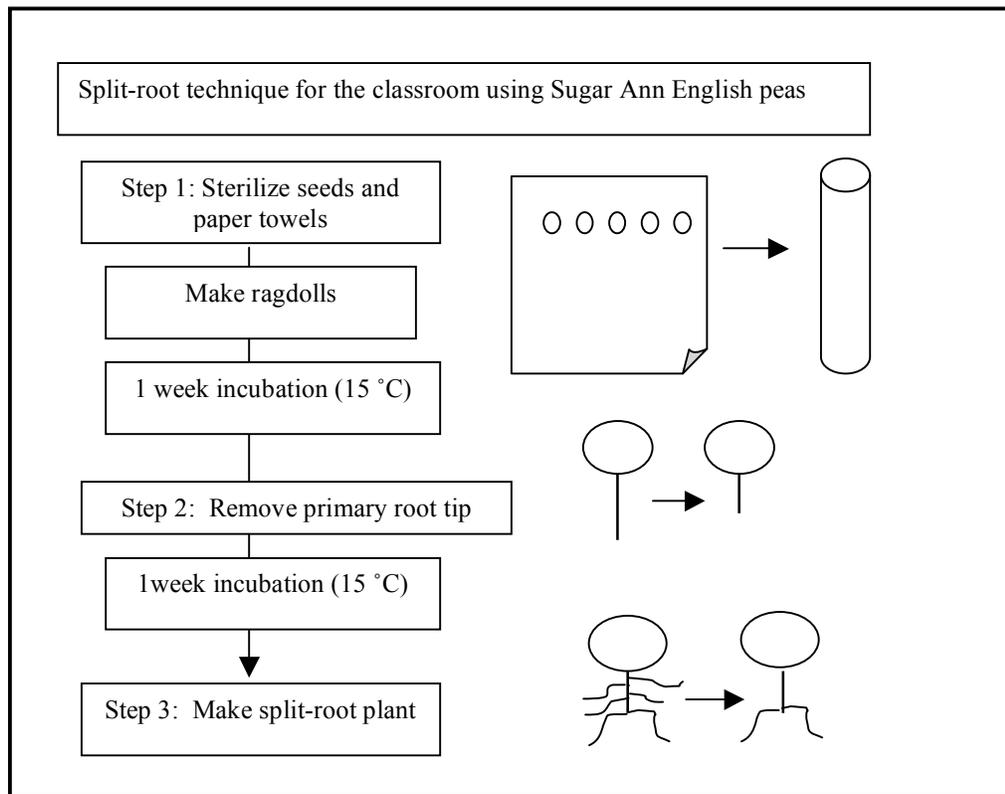
Figure 21. Modified split-root technique for the classroom.

Pilot Test with Fence-Sitters and Owners

Young split-root peas, created with the customized classroom methodology, are placed into fence-sitter and owner positions (Figure 19). This experiment, based on recent

literature (Maina et al., 2002), investigates root habitat selection models comparing root growth in competing plants (fence-sitters) and plants in isolation (owners). The null hypothesis states that the fence-sitters and owners are not different in regards to the root, shoot, and flower/fruit dry weights at maturity. Since the nutrient levels for fence-sitters and owners are equal, similar root mass is interpreted as a resource matching response. The alternate hypothesis is accepted when root, shoot, or flower/fruit dry weight is significantly different, demonstrating the plant response is not resource matching but either intra-plant avoidance or inter-plant avoidance response (Table 5). This comparison of dry weights for roots, shoots, and flowers/fruits involves summing the values for a pair of fence-sitters or a pair of owners and performing Hotelling's T^2 test, a multivariate test of differences between the mean values of two groups. Values less than $\alpha=0.05$ are considered to be significantly different.

In addition to dry weights, other quantitative data, including number of compound leaves, number of tendrils, number of flowers, and number of fruits are measured at weekly intervals, and mean values are graphed. Qualitative data is limited to overall plant appearance including color, degree of wilting, leaf curl, and necrosis.

Altogether, the experiment is repeated three times. In the first attempt, 60 split-root plants placed as 15 fence-sitter and 15 owner pairs are tested for time to maturity. Roots, shoots, and flowers/fruits of 3 samples randomly selected from each group are harvested after 2, 3, 4, 5, and 6 weeks of incubation. Harvested plant materials are dried at 75 ˚C for 1 week, and dry weights are compared statistically. The second repetition uses 80 split-root plants (20 paired plants per group) harvested at 4 weeks to test for sample size error and to determine reproducibility of data sets. Watering for each pot is

40 ml for the first trial and 60 ml for the second time of half strength Hoagland's medium (Hoagland & Arnon, 1950) 3 times a week. The third trial compares ambient light and environmental conditions in the greenhouse to laboratory and artificial light conditions used in the first two trials.

Trials one and two as well as several other experimental designs (fence-sitter versus single-root, split-root versus two single-roots, and two fence-sitters sharing a space), are placed under standardized light bench conditions (Figure 22) consisting of incubation at room temperature (24 ˚C) with continuous light emitted from a 4-bulb bank of cool white, 40 W fluorescent lamps suspended 61 cm above the plant bench. Plants are randomly positioned under the lamps so that treatment groups are interspersed and not separated by group.

Also, plants grown under the standardized light bench conditions are cultured in inexpensive 4-opening planting trays with each cavity measuring 6 x 4 x 6 cm; thus, each pair of fence-sitters occupies two openings or a total culture space of 288 cm^3. Each owner has a pot volume of 144 cm^3, but owners are treated in pairs, so the total pot volume is also 288 cm^3. All experimental pots contain inert vermiculite to avoid cation-anion effects of soil, and plants are supported by Velcro strips attached to wooden stakes available in grocery stores as shish-kabob skewers. Strips and stakes are sterilized in an autoclave.

Figure 22. Light bench conditions.

A third repetition of the fence-sitter versus owner experiment uses 60 plants (15 pairs per treatment) incubated in a greenhouse in early spring weather when ambient temperatures reach 30 ˚C. Hand watering with 60 ml of half strength Hoagland's medium (Hoagland & Arnon, 1950) occurs 3 times a week and every fourth watering is distilled water. Light intensity in the greenhouse measures 1,000-5,000 ft-c or 10,800-53,800 lux and far exceeds the illumination under the light bench conditions of 200 ft-c or 2,152 lux.

Other Experimental Designs

Four other experiments are analyzed for their potential use in the classroom and evaluated statistically using either the Hotelling's T^2 or paired-sample *t*-statistical tests. An original design eliminates vermiculite as a potting material and compares fence-sitters versus owners with their roots submerged in a liquid nutrient solution, Hoagland's

medium (Hoagland & Arnon, 1950). This liquid nutrient mixture contains all the macro-and micro- nutrients a plant requires for proper growth and is aerated to provide oxygen to the roots.

The null and alternative hypotheses for the fence-sitters and owners in the hydroponic design (Figure 23) are identical to the set-up utilizing vermiculite as well as the statistical test and alpha value. Like in the vermiculite pots, hydroponic plants are not independent; thus, each set of two plants (two fence-sitters or two owners) are treated as single samples; thus the dry weights for roots, shoots, and fruits of each pair are summed prior to analysis to avoid pseudoreplication. However, in the hydroponics setup, to statistically tolerate all plants located within a single aquarium, the fence-sitters and owners are blocked, meaning arranged into similar groups.
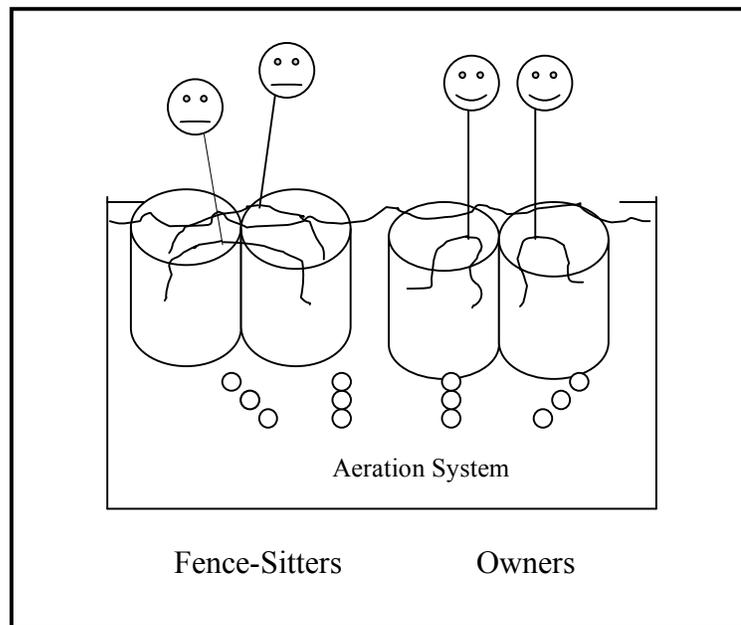
Figure 23. Hydroponics set-up for fence-sitters versus owners.

Two trials using 8 fence-sitter pairs and 8 owner pairs (32 plants total) for each attempt are cultured for 4 weeks in the unique hydroponic apparatus (Figure 24) specially designed for the experiment. The position of the aquarium under a bank of fluorescent lamps and the resulting light intensity differ between the first (125 ft-c or 1,345 lux) and second attempt (180 ft-c or 1,936 lux). Like the original vermiculite experiment, weekly above ground measurements and observational data are recorded with mean values graphed. Dry weights are also measured and statistically analyzed to decide whether to fail to reject or reject the null hypothesis. Habitat preference is determined by comparing outcomes with the habitat selection model (Table 5).

Figure 24. Modified aquarium for hydroponics experiment.

A modified 61 x 30.5 x 30.5 cm aquarium is filled with half strength Hoagland's medium (Hoagland & Arnon, 1950) incubated at 20 ˚C and aerated by bubbling

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compressed air. A drain valve, placed 2.5 cm above the base, facilitated weekly solution replacement. Thirty-two PVC pipes, 6 cm in diameter and 15 cm in length, are positioned vertically and raised 5 cm above the aquarium bottom to accommodate four-25.0 cm long air-stones that emit compressed air bubbles. The vertical tubes serve as plant holders, but plant support is supplemented with sterile skewers and Velcro tape. Approximately 60 cm above the top of the aquarium, a 4-bulb bank of cool white, 25 W fluorescent lamps are suspended and emit continuous light. The aquarium glass is wrapped in tinfoil to block light and algal growth, and the surface of the liquid medium is also covered with tinfoil to block light and prevent splattering. Vermiculite and hydroponic fence-sitter versus owner experiments are compared.

A second design modified from the literature (Gersani & Sachs, 1992) compares a fence-sitter with both roots intact to a fence-sitter with one of the twin root masses removed and designated as a single-root plant (Figure 16). This design investigates whether the single-root plant proliferates new root at a faster rate than the twin root plant when nutrients and space are identical.

The null hypothesis says the root, shoot, and flower/fruit masses for the fence-sitter and single-root plants are equivalent and assumes resource matching explains the expected outcome, that is, the rate of root growth is quicker in the single-root plants. The alternative hypothesis asserts that there is a difference between the two plant groups in dry weight or biomass of roots, shoots, or flowers/fruits. Each fence-sitter and each single-root plant is treated as a sample, and the statistical test employed is Hotelling's T^2 test with the alpha value set at 0.05.

The fence-sitter versus single-root experiments is repeated and data sets compared. Weekly, the number of leaves, tendrils, flowers, and fruits are measured as well as root, shoot, and flower/fruit dry weights at experiment termination. Qualitative observations on plant health, color, curling, and wilting are also recorded weekly. The first trial uses a sample size of 20, meaning 20 fence-sitters and 20 single-root plants, and tests whether plant maturity is reached after 4 or 5 weeks of incubation. Each pot is watered with 50 ml of quarter strength Hoagland's medium (Hoagland & Arnon, 1950) 3 times a week followed by pure distilled water on every fourth watering. For the second trial, the 20 fence-sitters and 20 single-roots receive 60 ml of half strength Hoagland's medium (Hoagland & Arnon, 1950) 3 times a week with the fourth watering, distilled water. The pot size, planting arrangement, incubation temperature, potting materials, lighting, and other parameters are identical to the light bench conditions described previously.

A second original design contrasts a split-root plant in a single pot to two single-root plants sharing one pot of an identical size (Figure 25). At zero time, pots for the fence-sitters and two single-root plants have equivalent root mass, but single-root pots support twice the shoot mass. The null hypothesis states root, shoot, and flower/fruit weights are equivalent for the split-root and paired single-root plants, while the alternative hypothesis asserts the weights are different. The appropriate statistical test is the Hotelling's T^2 test, and the dry weight biomass of the split-root plant is compared to the summed biomass for the single-root pair. This design, with a set alpha value of 0.05, explores whether competition plays a role when root masses are equivalent but shoot masses are not.
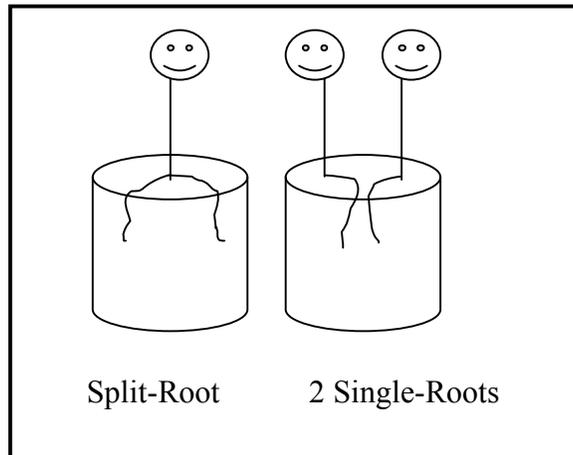
Figure 25. Split-root versus two single-root plants.

The first trial uses 18 sample units (18 split-root plants and 36 single-root plants) and tests timing of plant maturity with half of the plants harvested at 4 weeks and half at 5 weeks. Also, for the first attempt, each pot receives 40 ml of 0.25 strength Hoagland's medium (Hoagland & Arnon, 1950) 3 times a week followed by distilled water. The second trial, with a sample of 20 units (20 split-root plants and 40 single-root plants), tests plants watered with 50 ml of 0.5 Hoagland's medium (Hoagland & Arnon, 1950) 3 times a week per pot. For both trials, the usual quantitative and qualitative data are collected weekly, and plant organs are harvested at the end of the experiment for dry weight determination. The plants are placed under the light bench conditions and planted in 6 x 4 x 6 cm pots with vermiculite, sterile stakes, and Velcro and subjected to classroom randomized placement. Outcomes are compared to the habitat selection model (Table 5).

The third original design positions two fence-sitters so that each plant experiences intra-root and inter-root competition, i.e. competition with self and competition with roots

of a different pea plant, respectively (Figure 26). The null hypothesis states there is no difference in the dry root weights for intra- and inter-plant competitors, which might indicate that peas exhibit resource matching response (Table 5). On the other hand, the alternative hypothesis asserts that the weights of the summed isolated roots are different than the two roots in direct competition. The appropriate statistical test is the paired-sample-t test with an alpha value of 0.05 because only root biomass is compared.

Fence-sitters with one root competing and the second root in isolation
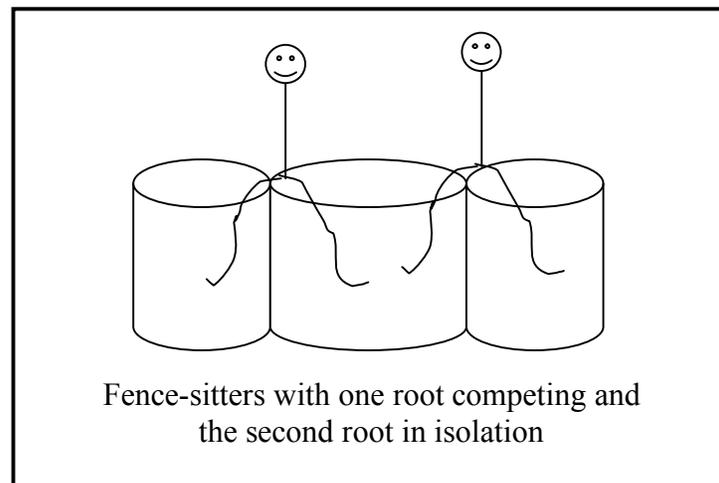
Figure 26. Two fence-sitters experiencing shared and unshared space simultaneously.

Modified planting trays with two smaller compartments (6 x 4 x 6 cm each) adjacent to a third compartment with twice the pot volume are used. Each fence-sitter has one root in a smaller pot and the other in the larger container. All plants are placed under light bench conditions. This experiment is repeated and watered each time with 0.5 strength Hoagland's medium (Hoagland & Arnon, 1950) 3 times a week with small pots receiving 40 ml and large pots 80 ml. Unlike other designs, the shoot and flower/fruit masses are not compared because the only treatment difference lay in the placement of the roots.

All five designs investigate root competition and habitat selection; however, other comparisons are feasible using split-roots. In anticipation of alternate student proposals in the classroom or as directed study research, some other possible plant placements are outlined and their research potential evaluated deductively.

Instructional Plan and Field Trials

While instructor-designs and tests of root competition experiments based on scientific research is a necessary task, the next phase, preparation for instruction, also is crucial. The plan for instruction is based on the steps of the ADDIE Model because it is straightforward and has perceived potential for adoption to laboratory teaching. During the analysis phase, student knowledge and skill level are determined and instructional objectives are identified prior to topic selection. In addition, composition of quality objectives is required. During the design phase, instructional strategies are selected and plans for addressing motivational issues are devised. For the former, the two prominent theories of knowledge in science education, objectivism and constructivism, are adopted as instructional strategies; consequently, two separate teaching experiences are planned. For motivational issues, strategies of Keller's ARCS Model (Keller, 1983) are incorporated. Another component of design is assessment of student learning through oral and written lab reports.

The fourth step, develop, involves the creation of instructional materials and schedules that are refined to meet the precise needs of the two teaching strategies, objectivism and constructivism. In the implement phase, two, unreplicated trials occur, one using the objectivist-approach and the other the constructivist-approach. Neither field

trial is designed for statistical analysis, but to gain some insight into project success, instructor observations and impressions are recorded as fieldnotes, and student surveys and lab reports are collected and evaluated. However, prior to student participation in the field trials, a plan for the ethical treatment of human participants is submitted to the University of West Florida Institutional Review Board (Appendix A) for approval. In this plan, students enrolled in Medicinal Botany (BOT4850) and Plant Biotechnology (BOT4734) are informed of the field study and their rights. Students are assured that their identities are protected and that they may ask questions before, during, or after their experience. In addition, they are advised there are no known risks associated with the study. Only students providing consent participate in the study (Appendix B).

Calculations and Evaluation of Results

In the ADDIE Model, evaluation occurs at all stages. For example, the scientific results produced by the instructor and students are evaluated to determine whether revisions should occur. Thus, evaluation occurs during each phase of the instructional design and implementation process and revisions made. Scientific evaluation is implemented as well, and for each root experiment either performed during the instructional design phase or by students, the quantitative data (i.e., number of leaves, tendrils, flowers, and fruits) are averaged for each parameter and graphed. The dry weights for the root, shoot, and flower/fruit biomass are compared using the Hotelling's T^2 test, except for the experiments involving two fence-sitters sharing a space where the paired-sample t-test is more appropriate. The Hotelling's T^2 test evaluates several means between two groups and generates a single p-value (Zar, 1999), which is compared to the

set alpha value of 0.05. The paired-sample *t*-test is employed for only one pair of means of two dependent groups. The single *p*-value produced is also evaluated against the set alpha value of 0.05. For both statistical tests, the null hypothesis is not rejected if the *p*-value is larger than the alpha value.

The teacher-tested and student-tested weekly growth data and dry weights are compared to each other. If graphs for leaf, tendril, flower, and fruit data have similar means and yields, then teacher and student data are assessed as equivalent. For the dry weight or biomass of roots, shoots, and flower/fruits, agreement of statistical tests for accepting or rejecting the null hypothesis is considered evidence that student and teacher-generated data are samples from the same experimental population and results are valid. Finally, data are compared to the root habitat selection model (Maina et al., 2002) to decide which type of competition applies (Table 5); and again, student and instructor outcomes must agree.

All qualitative data, including fieldnotes taken during class projects, are pooled and reviewed for potential patterns and hierarchies with any inconsistencies among data sources investigated. Deciding which themes to evaluate is the role of the instructor, but topics such as student interest, comprehension of fundamental knowledge, quality of experimental designs, and validity of methods for root competition are examined. The results of closed-ended questions on student evaluations are tabulated, averaged, and converted to percentages, while the open-ended questions are pooled with the qualitative observations of the instructor.

Science Model

In addition to creation of a root competition module and presentation of the lesson using two different instructional strategies, a major objective is the development of a model for selecting and modifying scientific research for the college teaching laboratory. Key components of the model, as any other instructional design plan, are goals for instruction and analysis of students. The proposed model includes criteria developed for topic and journal article selection; plus appropriate checklists are developed to quickly evaluate strong and weak points. The general outline employed to modify and test root competition experiments is translated into a stepwise procedure.

CHAPTER IV

RESULTS

The results of this study were organized in 4 parts: (a) five modified or original experimental design and test results, (b) an instructional plan, (c) field trial observations, and (d) a new model for adapting research to instruction in the college laboratory and recommended teaching strategies. Evaluation of student preparedness and steps leading to topic and species selection preceded testing the five experimental designs. Instructional plans for the five experiments, including handouts and schedules, were developed using the ADDIE Model as a guide for objectivist- and constructivist-based teaching strategies. Only general conclusions about the potential success of the experiments and instructional plans were drawn from comparison of data sets and observations made during single field trials of the objectivist and constructivist instructional designs. Finally, a model for transforming scientific research into projects suited to college classroom instruction was constructed using the logical progression of steps that gave the best results in the current study.

Instructor Generated Experimental Designs and Test Results

Results obtained by the instructor included analysis of the students and selection of a topic. In addition, five experiments were conducted and statistically analyzed.

Student Analysis

Prior to selecting a topic, student abilities and science curriculum were evaluated to be certain the degree of difficulty was appropriate and the selected subject enhanced the degree program. College students enrolled in upper-division botany courses had successfully completed at least one introductory botany course and lab, acquiring a familiarity with broad plant concepts, such as basic nutrition, plant anatomy, and competence in fundamental lab skills. A primary purpose of laboratory courses, especially upper-division sections, was direct experience with developing and testing concepts presented in lecture. The ability to investigate ideas using the scientific method was required for graduate school and scientific careers. Advanced botany courses endeavored to provide students with opportunities to culture plants, observe and measure growth, analyze and interpret data, communicate findings, and apply technological tools.

Topic Selection and Journal Article Criteria

Initial efforts involved selection of a topic from the literature that was complementary to the content of a college science course and the skill level of the enrolled students. Potential research topics were evaluated using the proposed checklist (Table 7). Two topics, root competition and phytochrome effects were evaluated in depth, and root competition was determined to best fit the selection model (Table 7). Roots were regularly studied in advanced, college level, botany courses, and root competition addressed many of the topics regularly described in lecture, including root anatomy, development, and function, role in plant nutrition, and root-shoot relationships. Literature on root competition and habitat selection models (Fallik et al., 2003; Gersani et al., 1998;

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Gersani et al., 2001; Gersani & Sachs, 1992; Maina et al., 2002) constitueds a cohesive

body of knowledge not yet fully explored in the research or classroom laboratories, thus

providing students with ample opportunity to practice critical thinking and produce

original work. While plant culture and manipulation required some care and skill, the

required facilities, equipment, and supplies were easily obtained. Technology and

statistical analysis waere routine methods applied to root competition studies, and the

relatively small space required for sufficient plant number bodes well for reproducible

results.

Table 7

Criteria for Topics Potentially Amenable to Classroom Adoption

Criteria	Proposed Topic	
	Root Competition	Phytochrome
Cohesive, Small Body of Knowledge	√	√
Part of a Larger Course Topic	√	√
Meets Learning Objectives	√	√
Improves Student Skills	√	√
Adapts to Classroom Meeting Schedule	√	X
Equipment and Facilities Available	√	X
Supplies Affordable	√	X
Potential for Student-Designed Experiments	√	√
Incorporates Student Use of Technology	√	√
Uses Statistical Analysis	√	√
Potential for Reproducible Results	√	√

Note. √ = met and x = not met.

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Species Selection

A major obstacle to modifying recent root competition studies for the classroom was identifying a readily available plant species that reliably forms split-root plants, that is, plants with twin root masses. To address this problem, seeds from five readily available species were germinated and tested for their ability to form split-root plants using a protocol modified from the literature (Figure 20a), and subsequently, evaluated for species hardiness and life cycle length (Table 8). After 1 week, only peas (*Pisum sativum*) and lima beans (*Phaseolus lunatus*) yielded split-root plants. The roots of tomatoes (*Lycopersicon esculentum*) and cucumbers (*Cucumis sativus*) were too short to withstand tip excision, and too many lateral roots formed in the corn plants (*Zea mays*) prior to removing the primary root tip. With more than 1 week of incubation, the tomato and cucumber germlings may have proved suitable, but classroom scheduling required a short response time.

Table 8

Completed Checklist for Scoring Plants on Selection Criteria

Species	Readily Available	Hardy	Days Until Harvest*	Forms Split-Roots	Split-Root Efficiency	Split-Root Survival
Pea	√	√	75	√	25%	100%
Cucumber	√	√	60	X	0%	0%
Lima Bean	√	√	75	√	10%	25%
Tomato	√	√	65	X	0%	0%
Corn	√	√	75	X	0%	0%

Note. √ = yes, and x = no. * = information from Burpee (seed supplier) website.

Even though peas and beans formed split-roots, peas had two important advantages (Table 8). Of the 40 pea seeds planted, 10 formed split-root plants, an efficiency of 25% and equivalent to results reported in the literature (Gersani et al., 1998). In addition, 100% of the split-root pea plants survived manipulations and reached maturity. Only four split-root lima beans were formed with an efficiency rate of 10%, but only one survived for a 25% survival rate at maturity (Table 8).

Classroom Split-Root Technique

The protocol for the split-root technique described in science literature (Figure 20, column a) and used to select peas as the plant of interest was not practical for a teaching laboratory that meets weekly. Four protocols (Figure 20, columns b-e) that reduced teacher responsibility and planned to time events at 1-week intervals were designed and differed on use of aeration, intervals between events, soil medium, and temperature.

Even though each procedure produced split-root peas, there were differences in teacher and student responsibility as well as split-root efficiency (Table 9). In the first and second protocols (Figures 20, columns b & c), the teacher sterilized, aerated, and planted seeds in ragdolls two days in advance of the class meeting, and thus, teacher duties were rated as high. Students cut the root tips, and a week later, the secondary root tips. Both protocols employed ragdolls that were easily unrolled for severing the primary root tip and secondary roots, and separation of roots from paper towels caused less damage than unearthing and replanting vermiculite-grown plants.

Although the teacher and student tasks were similar for the two protocols, split-root efficiency differed. The first protocol (Figure 20, column b) had a 25% efficiency

rate and 100% survival rate, while the warmer temperature of the second protocol (Figure 20, column c) increased fungal contamination of the cotyledons, decreasing split-root efficiency rate to 10%, although 100% of the split-root plants survived.

In the third protocol (Figure 20, column d), teacher preparation was rated as intermediate because the teacher sterilized and aerated seeds, but the students removed the primary root tip and secondary roots, yielding an efficiency of 25% and 100% survival rate in these vermiculite-germinated seedlings (Table 9). Unearthing vermiculite embedded roots for excisions caused root injuries and required participants to wear masks to avoid inhaling air-borne vermiculite particles, a danger to respiratory health. By comparison, the ragdoll incubation for seed germination was safer and caused less root damage.

The fourth protocol (Figure 20, column e) reduced teacher preparation to sterilizing seeds; thus, students were responsible for germinating seeds in ragdolls, making split-root plants, using ragdolls and using a cold temperature (15 ˚C) incubation to decrease fungal contamination and slow growth rate. The fourth protocol with its 25% efficiency and 100% survival rates was ideal for the teaching laboratory that meets weekly (Figure 21). All future experimental designs used this protocol (Figure 20, column e).

Table 9

Teacher Responsibility and Split-Root Efficiency and Survival Rates for Four Protocols

Protocol Number	Teacher Responsibility	Efficiency Rate for Split-Root Induction	Survival Rate for Split-Root Plants
20 b	High	25%	100%
20 c	High	10%	100%
20 d	Medium	25%	100%
20 e	Low	25%	100%

Note. Protocol numbers are from Figure 20.

Root Competition Experiments

Using peas and the classroom modified split-root technique, five instructor-designed and tested experiments investigated root competition: (a) fence-sitters versus owners (adapted from Maina et al., 2002), (b) hydroponic fence-sitters versus owners (original design), (c) fence-sitter versus single root (modified from Gersani et al., 1992), (d) split-root versus two single roots (original), and (e) two fence-sitters sharing a space (original).

Fence-Sitters Versus Owners. The first design (Figure 19), adapted from the literature (Maina et al., 2002) and tested through three trials, investigated intra- and inter-root competition. The first attempt examined the feasibility of the design and time span to plant maturity using 15 paired plants. Each pair of plants was treated as one sample, and three samples were randomly harvested at weekly intervals from the second to sixth week after planting split-roots in vermiculite. Means for weekly measurements of compound

leaves (Figure 27) and tendrils (Figure 28) were similar for fence-sitters and owners

throughout the 6-week period. In the first 4 weeks, leaves and tendrils increased almost

linearly for both treatments yielding about 20 leaves per sample. Tendrils were the last

part of the compound pea leaf to unroll and were visible toward the end of leaf

development, an observation most apparent at the end of the first week (Figures 27 & 28)

when 7 leaves but only 5 tendrils were counted. By week 6, only 21 leaves per sample

were recorded, just one more leaf than measured at week 4 (Figure 27). Apparently, the

pea plants reached vegetative maturity after about 4 weeks of incubation on the lighted

lab bench.
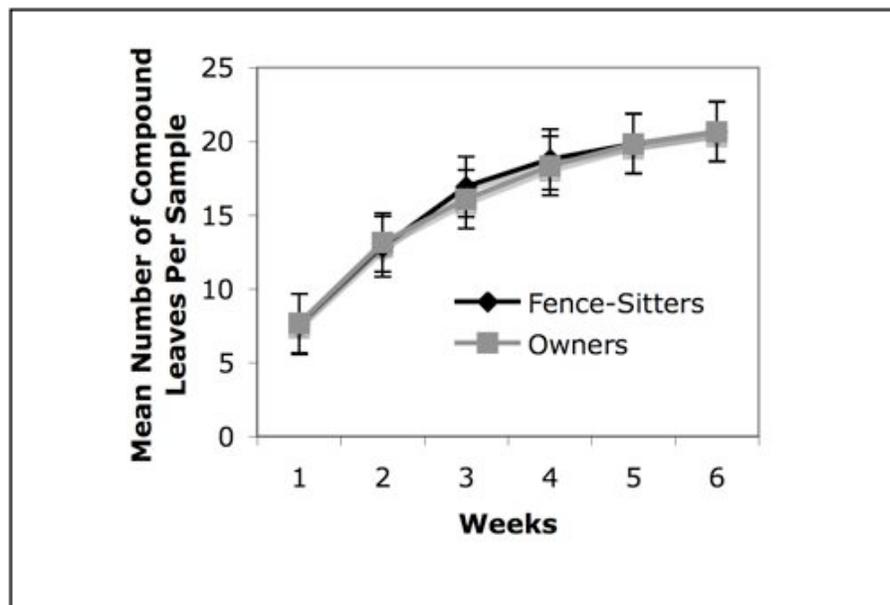
Figure 27. Mean number of compound leaves per sample in weekly measurements for fence-sitters versus owners, trial one.
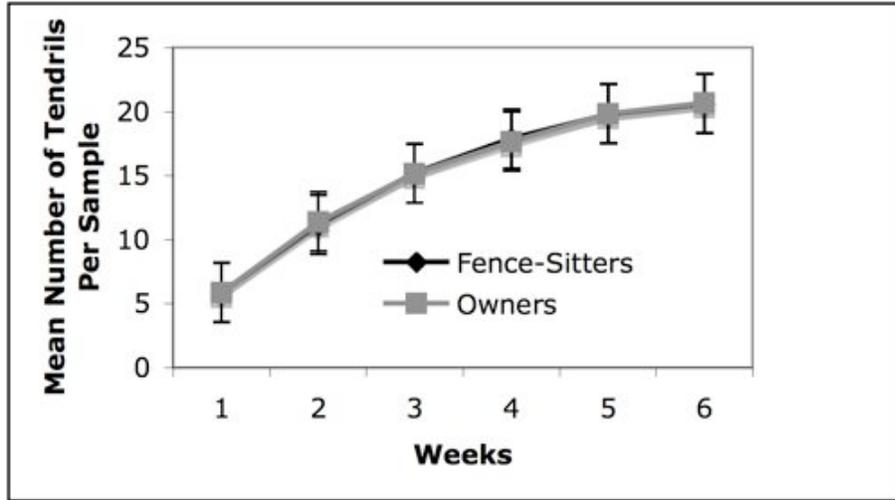
Figure 28. Mean number of tendrils per sample in weekly measurements for fence-sitters versus owners, trial one.

Flowers were visible at the third week and fruits at the fourth week (Figures 29 & 30). The mean number of flowers and fruits were similar for the fence-sitters and owners throughout the experiment. The largest number of flowers were recorded at the third week with a steady decline thereafter, while the largest number of fruits occurred at weeks 5 and 6 when flowers gave way to fruit formation (Figures 29 & 30). In the interest of conserving classroom time, termination of the experiment at 4 weeks provided a combination of flower and fruit data sufficient to assess reproductive alternations potentially caused by root competition.
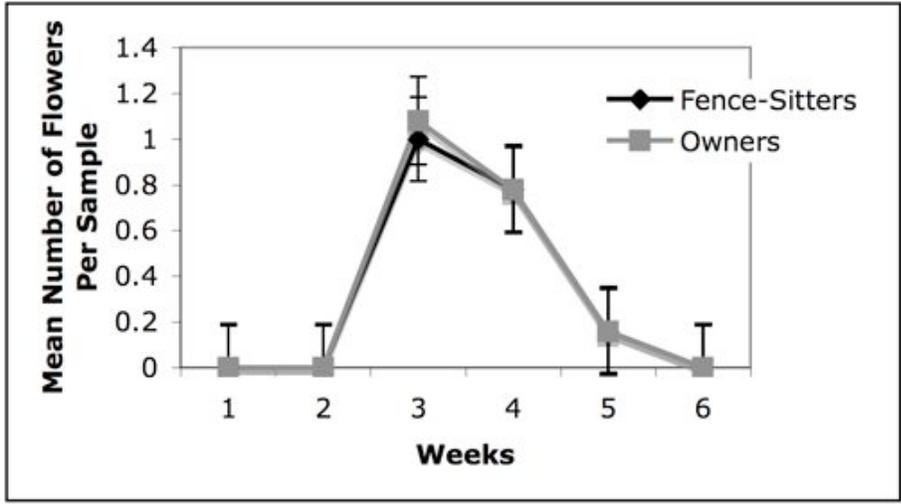
Figure 29. Mean number of flowers per sample in weekly measurements for fence-sitters versus owners, trial one.
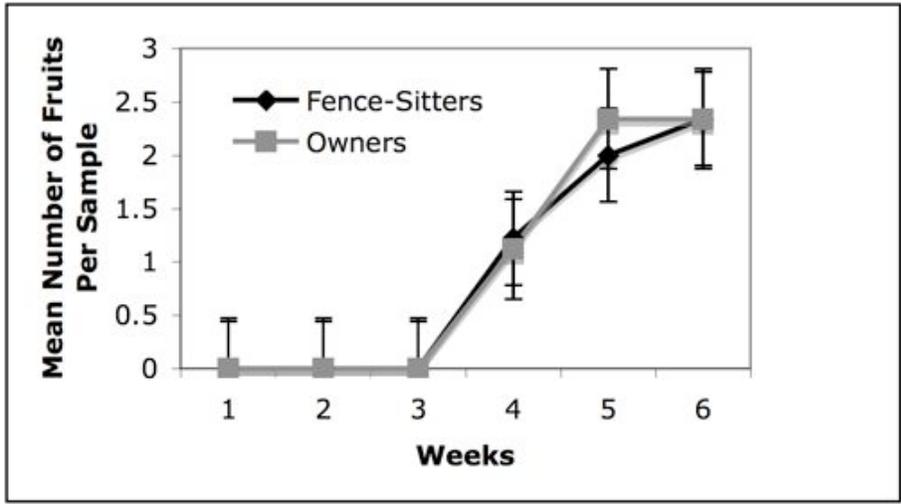
Figure 30. Mean number of fruits per sample in weekly measurements for fence-sitters versus owners, trial one.

All plants appeared green and healthy every week; however, some wilting and a general dryness of the vermiculite were recorded. Raising the quantity of liquid from 40 ml of 0.5 strength Hoagland's medium (Hoagland & Arnon, 1950) per pot was indicated for subsequent experiments.

Each week, starting with the second week, three random sample units were harvested, dried, weighed, and averaged for each group (Table 10). In addition to the calculation of means and standard error for dry weights, the root-shoot ratio for each week was computed (Table 11) and graphed (Figure 31). The relationship between root-shoot ratios for the two treatments were similar on a week-by-week basis, but over the 6 week period, root mass appeared to increase at a faster rate than shoot mass for both treatments (Figure 13).

Table 10

Mean Dry Weights and Standard Errors in Fence-Sitters Versus Owners, Trial One

| | Dry Weights | | | | | |
| | Root (g) | | Shoot (g) | | Flower/Fruit (g) | |
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Week 2						
Fence-Sitters	0.083667	0.012387	0.420667	0.001856	0	0
Owners	0.104000	0.019399	0.468667	0.034338	0	0
Week 3						
Fence-Sitters	0.121333	0.018800	0.484333	0.059145	0	0
Owners	0.125000	0.006110	0.491667	0.007535	0	0
Week 4						
Fence-Sitters	0.227667	0.020851	0.774000	0.045938	0.259333	0.046520
Owners	0.140000	0.001155	0.628333	0.024443	0.217333	0.029294
Week 5						
Fence-Sitters	0.193000	0.011015	0.754000	0.037242	0.672667	0.085450
Owners	0.176333	0.024606	0.738667	0.098208	0.478000	0.104290
Week 6						
Fence-Sitters	0.157000	0.023159	0.592667	0.046692	0.794000	0.129129
Owners	0.157333	0.009062	0.479667	0.055921	0.738000	0.019655

Note. Sample size = 3 for each week, $\overline{X}$=mean per sample, and SE=standard error.

Table 11

Root-Shoot Ratios for Fence-Sitters Versus Owners, Trial One

Time	Root-Shoot Ratios	
	Fence-Sitters	Owners
Week 2	0.199	0.222
Week 3	0.251	0.254
Week 4	0.294	0.223
Week 5	0.256	0.239
Week 6	0.265	0.328
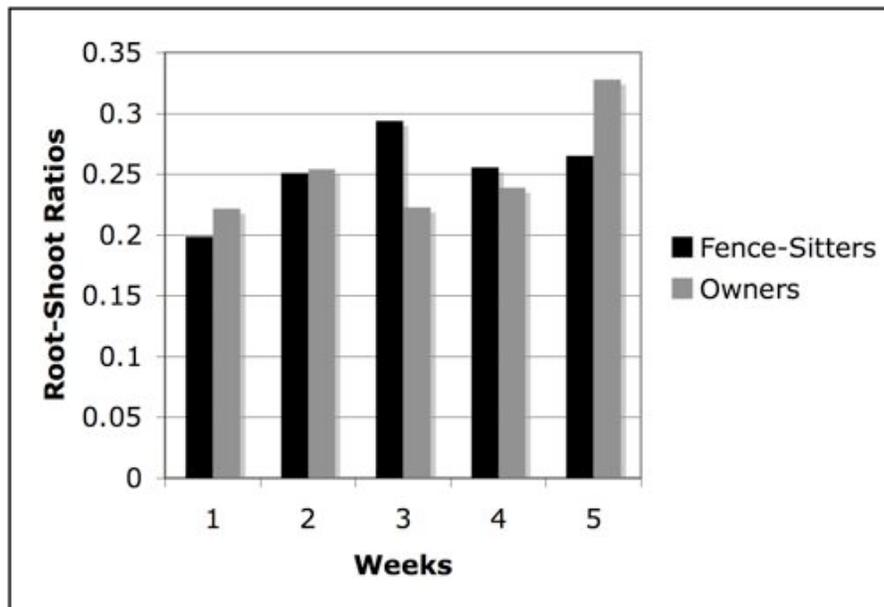
Figure 31. Root-shoot ratios per sample in weekly measurements for fence-sitters versus owners, trial one.

The mean dry weights for roots, shoots, and flowers/fruits appeared similar for both treatments (Table 10) but were subjected to the Hotelling's T^2 test to verify this

assumption. The null hypothesis claimed there was no difference in the dry weights between fence-sitters and owners, while the alternative hypothesis asserts that there was a difference. For each week, the single *p*-value generated was well above the alpha value set at 0.05 with the lowest *p*-value at 0.145670 and the highest *p*-value at 0.985458 (Table 12); thus, statistically there was no dry weight or biomass difference between groups. The null hypothesis was not rejected; however, the wide variation among weekly *p*-values indicated that a sample size larger than three must be tested. Overall, the fence-sitters and owners were behaving similarly, and the fourth week, when there was a mixture of flowers and fruits, once again showed to be the shortest time interval for assessing both vegetative and reproductive maturation and was the experimental interval selected for subsequent experiments.

Table 12

Hotelling's T^2 Test Values for Dry Weights in Fence-sitters v Owners, Trial One

	Hotelling's T^2 Test Values			
	df1	df2	F	*p*
Week 2	2	3	0.733	0.550600
Week 3	2	3	0.015	0.985458
Week 4	3	2	6.024	0.145670
Week 5	3	2	1.634	0.401527
Week 6	3	2	0.589	0.678686

Note. Sample size = 3 for each week, df = degrees of freedom, F = test statistic, *p* = *p*-value.

Based upon results from the first trial, the experiment was repeated with a larger sample size to confirm outcomes. Twenty samples (2 plants each) of fence-sitters and

owners were incubated for 4 weeks and watered with 60 rather than 40 ml of 0.5 strength

Hoagland's medium (Hoagland & Arnon, 1950). All the same weekly measurements as

trial one were taken, but plants were harvested only at 4 weeks for dry weights.

While the sample number for this trial was larger, trends were similar to the first

attempt. The mean number of compound leaves and tendrils increased linearly over the 4-

week period for fence-sitters and owners, just as it did in the first trial (cf. Figures 27, 28,

32, & 33). For the second trial, there was less difference in mean values for leaves and

tendrils when compared to the first attempt, and total leaf number reached 20 per sample,

just as it did in trial one.
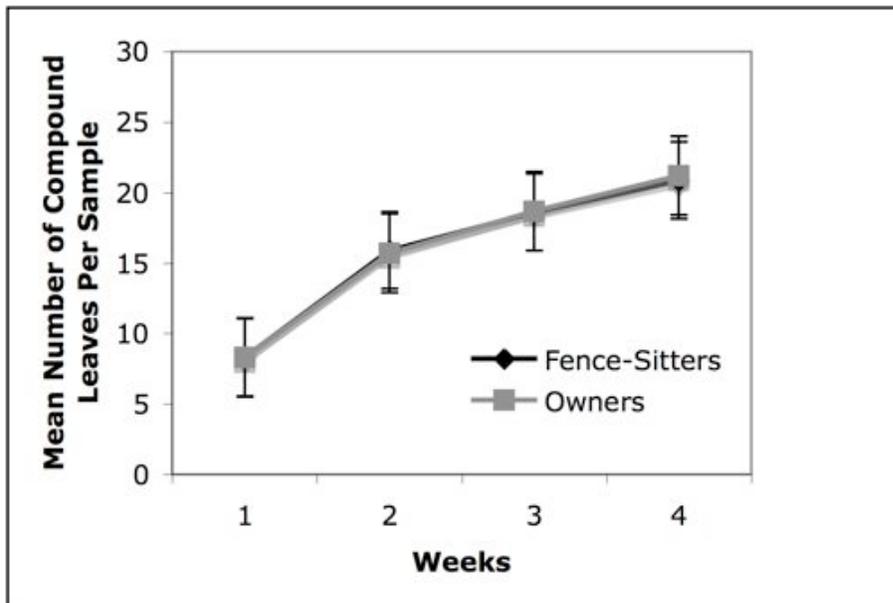
Figure 32. Mean number of compound leaves per sample in weekly measurements for
fence-sitters versus owners, trial two.
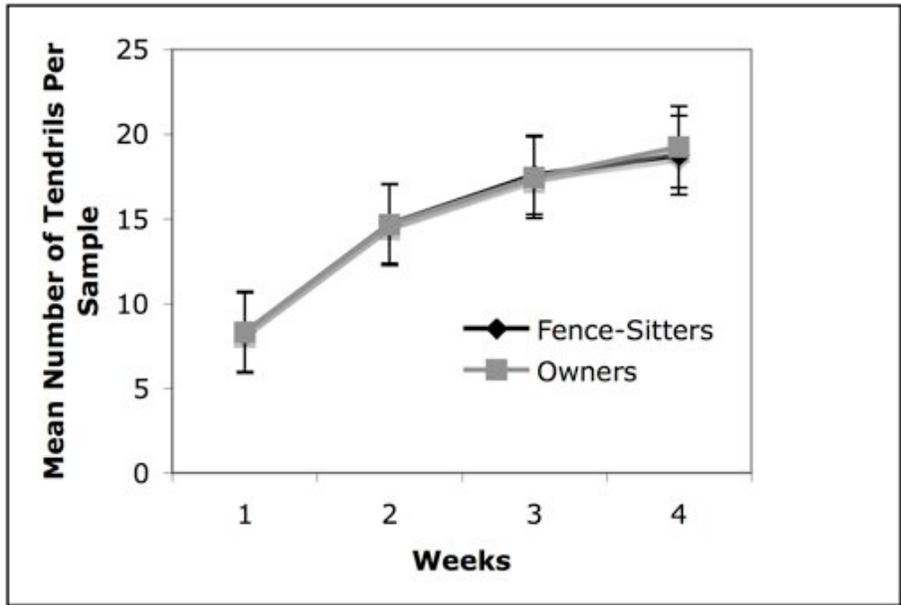
Figure 33. Mean number of tendrils per sample in weekly measurements for fence-sitters versus owners, trial two.

Flowering occurred in the third week in both groups and in both trials (Figures 29 & 34). For the second trial, the mean number of flowers decreased in both groups by the fourth week because of the transition to fruit and seed production. Although the fence-sitters had a mean number of flowers slightly larger than the owners in the fourth week, the results were in general agreement with the first attempt showing that the fence-sitters and owners were flowering and reaching maturity within the same time frame and with the same frequency.
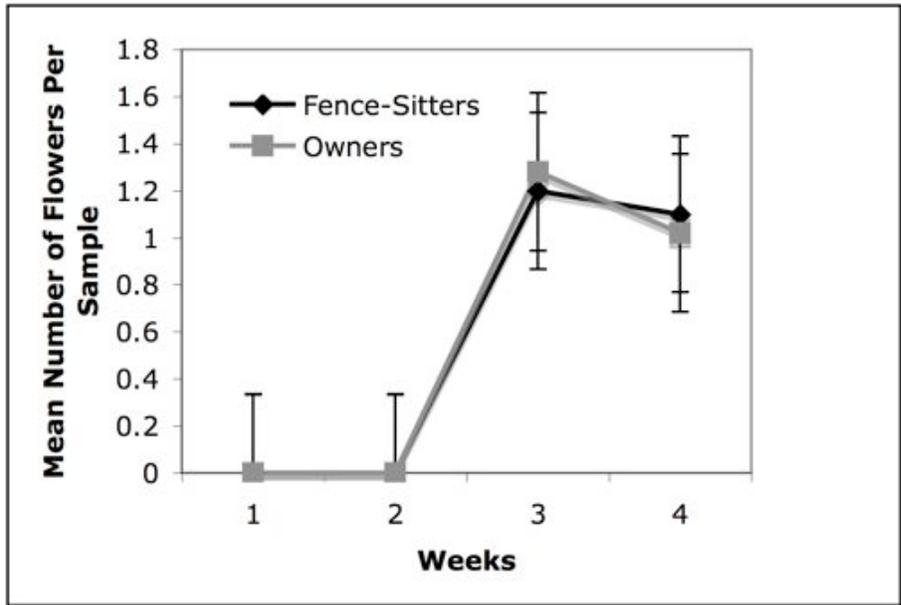
Figure 34. Mean number of flowers per sample in weekly measurements for fence-sitters versus owners, trial two.

Unlike in the first attempt, fruit production started in the third week for both the fence-sitters and owners (Figure 35) instead of the fourth week (Figure 30). Besides harvest date, the only variables that differed between trial one and trial two were the 50% increase in water and available nutrients, which might have accounted for the observed differences. Although the mean values for fruits in trial two were relatively low at week 3, by the fourth week nearly every plant had one pod in both groups, and the increase in fruits coincided with the decline in flowers (cf. Figures 34 & 35). All plants were green and healthy throughout the 4 weeks with no deaths and were more turgid than in the first trial, confirming the perceived need for more water.
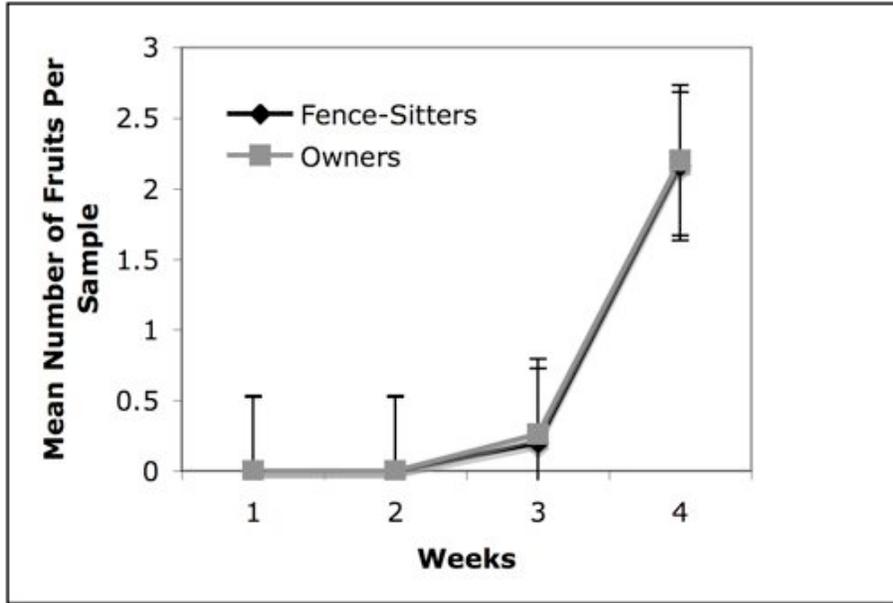
Figure 35. Mean number of fruits per sample in weekly measurements for fence-sitters versus owners, trial two.

The mean values and standard errors for 4 week dry weights were computed (Table 13), followed by application of the Hotelling's T^2 test to investigate significant differences. All dry weights were pooled by group, and the statistical test yielded $\underline{F}$ (3, 36)= 0.602 corresponding to a *p*-value of 0.617665 (Table 13). This *p*-value was similar to the first trial, well above the preset alpha value of 0.05, thus, confirming no statistical difference between the two treatments. The small values for standard error in the second trial indicated a sample size of 20 was sufficient (Table 13). Both trials when compared to the habitat selection model corresponded to the resource matching response (Table 5).

Table 13

Mean Dry Weights and Standard Errors, p-Values, and Root-Shoot Ratios in Fence-Sitters Versus Owners, Trial Two

| | Dry Weights | | | | | |
| | Root (g) | | Shoot (g) | | Flower/Fruit (g) | |
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Fence-Sitters	0.164800	0.008378	1.078650	0.045685	0.156500	0.017992
Owners	0.177200	0.009187	1.081550	0.053398	0.136750	0.018059
p-value = 0.617665						
Root-Shoot Ratios		Fence-Sitters = 0.153		Owners = 0.164		

Note. Sample size = 20, $\overline{\overline{X}}$ = mean per sample, and SE = standard error.

The root-shoot ratios were calculated for fence-sitters and owners at 0.153 and 0.164, respectively (Table 13). The ratios were similar for both groups, but were smaller than reported for the first trial (Table 11); moreover, comparison of dry weight means at 4 weeks confirmed extra shoot production in trial two. The 50% increase in water and nutrients in trial two probably accounted for the extra shoot mass.

The third trial for the fence-sitters versus owners tested whether greenhouse incubation under natural light, photoperiod, and temperature regimes affected experimental outcomes. Addressing this concern determined the validity of performing the experiment in the classroom with constant temperature and fluorescent light banks. Again, plants were observed and measured weekly but harvested at 4 weeks. The sample size was reduced to 15 units (pairs) per group to accommodate available greenhouse space.

Similar to trials one and two, there was little difference in the above-ground data between fence-sitters and owners for all 4 weeks. The mean values for compound leaves and tendrils were nearly identical for both groups (Figures 36 & 37). The greatest difference between leaf and tendril values occurred in the second week; however, the interval was extremely small. The yields for leaf formation in trials one and two (Figures 27 & 32) were greater, about 20 leaves per sample, than trial three (Figure 36), about 17 leaves per sample, and may be attributed to greater variability in environmental conditions in the greenhouse, including low over-night temperatures and light intensity that oscillates with cloud cover. Based on leaf and tendril production, light bench conditions in the laboratory provided an adequate incubation environment.
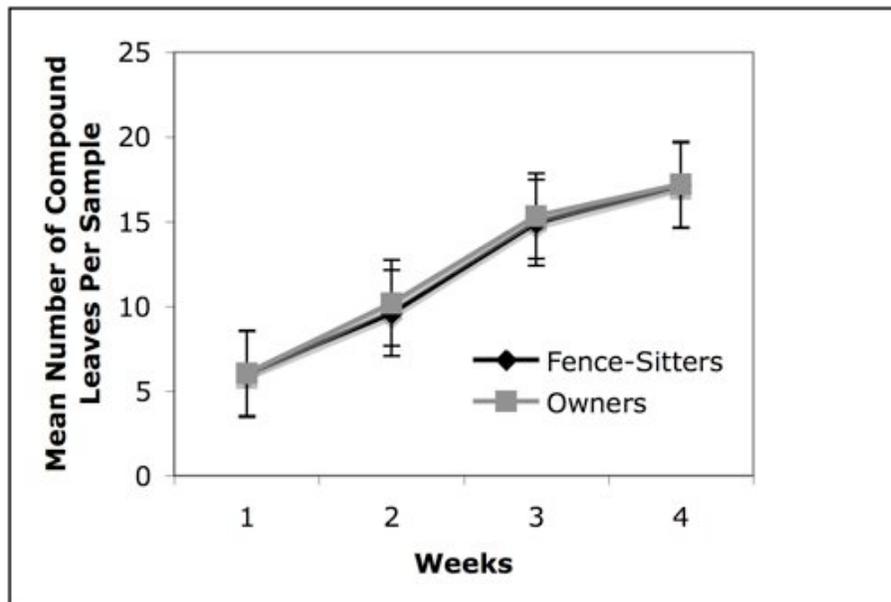
Figure 36. Mean number of compound leaves per sample in weekly measurements for fence-sitters versus owners grown in the greenhouse, trial three.
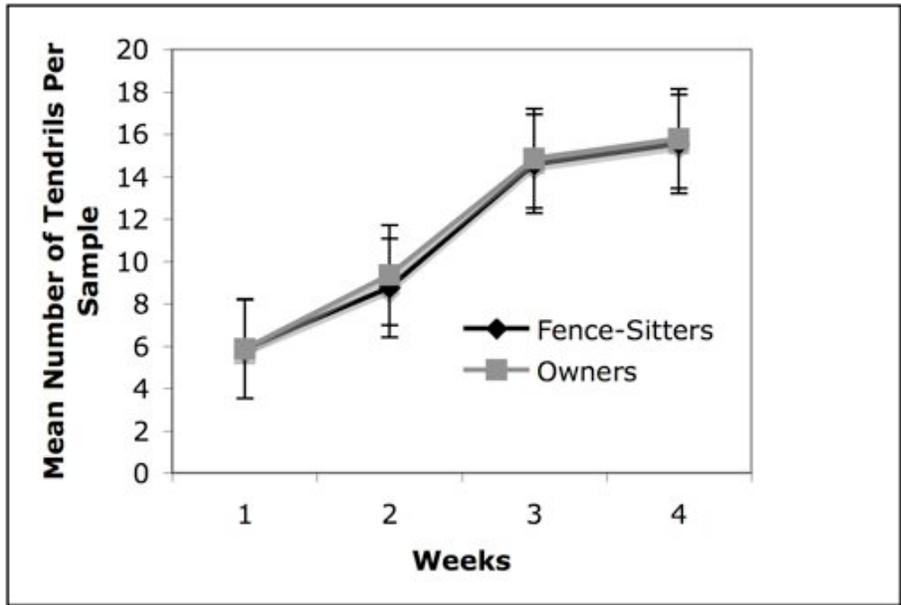
Figure 37. Mean number of tendrils per sample in weekly measurements for fence-sitters versus owners grown in the greenhouse, trial three.

Unlike in the other attempts, fence-sitters and owners did not produce flowers until the fourth week (Figure 38), and even at this point, the mean value for both groups was very low, 0.35 flowers per sample compared to 1.0 and 1.2 per sample at week 3 for trials one and two, respectively (Figures 29 & 34). The later initiation of flowering must be related to changed environmental conditions rather than root competition because comparison of fence-sitters and owners in trial three showed a nearly identical response to greenhouse conditions.
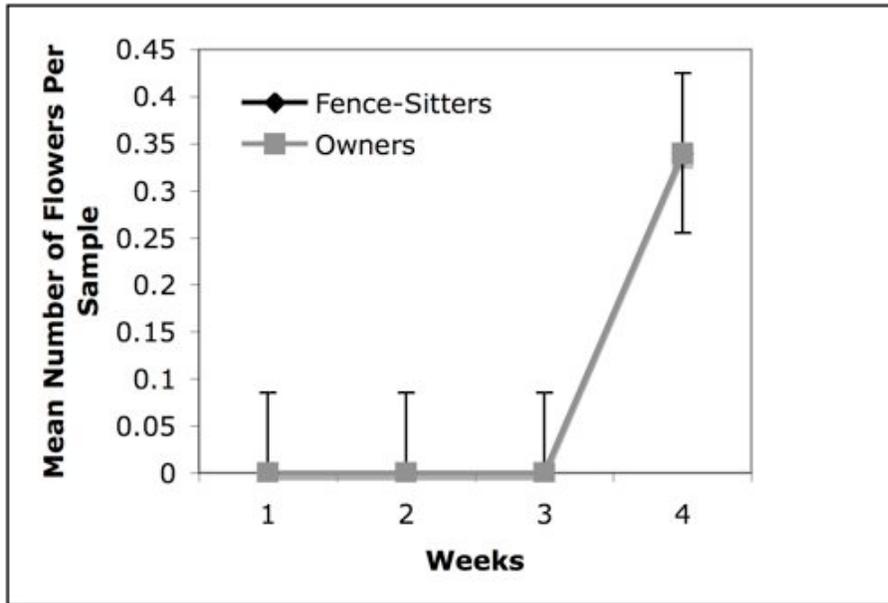
Figure 38. Mean number of flowers per sample in weekly measurements for fence-sitters versus owners grown in the greenhouse, trial three.

By the fourth week few plants had flowers, but none had fruits, so the harvest of plant parts for biomass or dry weights excluded fruit (Table 14). Comparison of dry weights using the Hotelling's T^2 test yielded $\underline{F}$ (3, 26) =1.292 with a corresponding *p*-value of 0.298011. Like the other trials, there was no difference in biomass between fence-sitters and owners, when $\alpha = 0.05$. Also, like trials one and two, application of the habitat selection model (Table 5) indicated roots of peas compete in the greenhouse fence-sitters and owners experiment using the resource matching response.

Table 14

Mean Dry Weights and Standard Errors, p-Values, and Root-Shoot Ratios in Fence-Sitters Versus Owners, Trial Two

| | Dry Weights | | | | | |
| | Root (g) | | Shoot (g) | | Flower (g) | |
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Fence-Sitters	0.123800	0.008088	0.790333	0.030781	0.012467	0.005436
Owners	0.137400	0.004601	0.881000	0.034503	0.011800	0.003279
p-value = 0.298011						
Root-Shoot Ratios		Fence-Sitter = 0.157		Owners = 0.156		

Note. Sample size = 15, $\overline{X}$ = Mean, and SE = standard error.

Using biomass values, the root-shoot ratios were computed (Table 14) as 0.157 for fence-sitters and 0.156 for owners, similar values to those reported in trial one, 0.153 and 0.164, respectively (Table 13). These low values represented plants allocating more nutrients to shoot production than root production.

In conclusion, the adapted fence-sitter versus owner experiment corresponded to resource matching within the habitat selection model (Table 5) in all three trials. Fifteen to twenty samples per group, 60 ml of 0.5 strength Hoagland's medium (Hoagland & Arnon, 1950) 3 times a week, and a 4-week incubation period under light bench conditions in the laboratory yielded reproducible results. Greenhouse-grown plants under more natural light and temperature conditions required a longer incubation period to reach maturity, but results generally agreed with lab trials. All in all, the light bench protocol seemed better suited to the teaching laboratory.

Hydroponic Fence-Sitters Versus Owners. Instead of using vermiculite, fence sitters and owners were grown in a hydroponic environment (Figure 23). The initial pilot study failed due to an overgrowth of algae on the cotyledons, leaves, and wooden skewers used to stake the split-root plants. Algal growth was greatly reduced in a second attempt when the outside of the aquarium was covered by aluminum foil to prevent light from reaching the liquid medium. The skewers were sterilized prior to use, and the top of the medium was covered with foil to stop water from splashing on the skewers and leaves, thus, eliminating the damp surface ideal for algal growth. Once these initial problems were solved, two 4-week trials of fence-sitters versus owners in the hydroponic apparatus were tested.

For the first attempt, the mean number of compound leaves were nearly identical for fence-sitters and owners each week and increased in a linear fashion (Figure 39). The mean number of tendrils were also similar from week to week, and like the compound leaves, the tendrils increased linearly (Figure 40). Results for compound leaves were consistent with those reported for vermiculite-grown plants (cf. Figures 32 & 39), yielding about 20 leaves per sample by week 4.

Figure 39. Mean number of compound leaves per sample in weekly measurements for hydroponic fence-sitters versus owners, trial one.

Figure 40. Mean number of tendrils per sample in weekly measurements for hydroponic fence-sitters versus owners, trial one.

Flowering first occurred in the third week (Figure 41), just as it did in vermiculite-grown plants (Figure 34); however, the mean number of flowers averaged 0.4 per sample (Figure 41) rather than 1.2 for vermiculite-grown plants (Figure 34). Flower number increased in the fourth week for hydroponic plants, yielding only 0.9 flowers per sample (Figure 41). Like the vermiculite trials, flowers were formed at a similar rate for hydroponic fence-sitters and owners (Figure 41). Fruits did not appear until the fourth week (Figure 33), differing from the second vermiculite experiment (cf. Figures 35 & 42), where a few fruits were counted in week 3. Fruits were formed at a similar rate for fence-sitters and owners; however, fruit yield measured 0.6 per sample for hydroponic plants but 2.2 for vermiculite-grown plants, mirroring the lower yields for hydroponic flowers. The slower maturation of hydroponic plants may have reflected differences in environmental conditions.

Figure 41. Mean number of flowers per sample in weekly measurements for hydroponic fence-sitters versus owners, trial one.
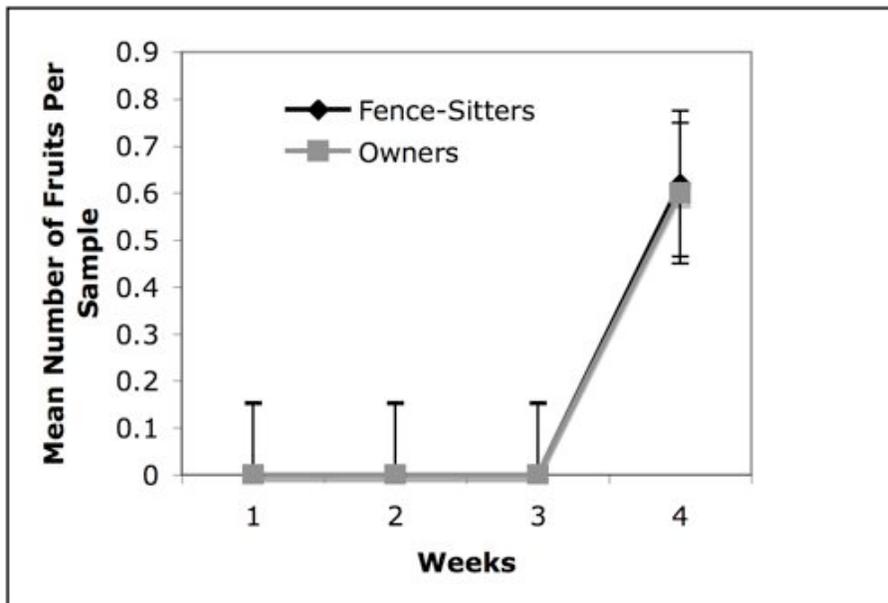
Figure 42. Mean number of fruits per sample in weekly measurements for hydroponic fence-sitters versus owners, trial one.

Unlike the initial hydroponic pilot study, the plants and skewers had little algal contamination; thus, addition of foil and sterile skewers to the hydroponic apparatus eliminated algal growth. Throughout the experiment, the plants appeared green, turgid, and healthy indicating the weekly replacement of 0.5 strength Hoagland's medium (Hoagland & Arnon, 1950) maintained a sufficiently high nutrient concentration.

After 4 weeks, the roots, shoots, and flowers/fruits for both groups were harvested, dried, and averaged (Table 15). The results of the Hotelling's T^2 test yielded $\underline{F}$ (3, 12) = 0.082 with a corresponding *p*-value of 0.968797. Consequently, the null hypothesis was not rejected because biomass for the fence-sitters and owners was not different. In contrast, hydroponic root and shoot biomass (Table 15) measured about half of that of vermiculite-grown plants (Table 13), but flower and fruit biomass was far less

in hydroponic trials, yielding only 15% of the mass recorded for vermiculite-grown

plants (cf. Tables 13 & 15). Like biomass, calculated root-shoot ratios for hydroponic

fence-sitters and owners were also similar, 0.169 and 0.161, respectively (Table 15),

illustrating that both groups were allocating resources in an equivalent pattern.

Comparison with vermiculite trial two showed similar root-shoot ratios, 0.153 and 0.164

(Table 13), to hydroponic plants (Table 15); thus, resources were allocated in the same

proportions for vegetative biomass whether peas were raised in a solid or liquid medium.

According to the habitat selection model (Table 5), resource matching governed the root

competition response.

Table 15

Mean Dry Weights and Standard Errors, p-Value, and Root-Shoot Ratios for Hydroponic Fence-Sitters Versus Owners, Trial One

	Dry Weights					
	Root (g)		Shoot (g)		Fruit (g)	
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Fence-Sitters	0.080000	0.006018	0.474250	0.030059	0.022500	0.005994
Owners	0.076500	0.010502	0.473750	0.060769	0.022500	0.005994
p-value=0.968797						
Root-Shoot Ratio		Fence-Sitters=0.169		Owners=0.161		

Note. Sample size = 8, $\overline{X}$ = mean, and SE = standard errors.

Although peas had similar ratios for vegetative growth in liquid medium and

vermiculite, a major difference was the delay in fruiting and smaller flower/fruit biomass

in hydroponic peas. Incubation conditions for hydroponic culture were re-evaluated, and

the lighting was improved by centering the aquarium under the fluorescent lamps to

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increase light intensity from 1,345 lux to 1,936 lux, still slightly less than the intensity of vermiculite-grown plants. With lighting more comparable to the vermiculite-grown plants, the hydroponics experiment was repeated with 8 sample units per group to investigate whether the timing for fruiting continued to be delayed.

For the second trial with improved light distribution, the mean number of compound leaves and tendrils (Figures 43 & 44) were similar for the fence-sitters and owners and mirrored results of the first hydroponic attempt (Figures 39 & 40) with leaves and tendrils increasing linearly and peaking at 20 leaves per sample like trial one. The agreement between leaf and tendril yields for fence-sitters and owners from the two hydroponic trials indicated the small changes in light conditions had little effect on shoot development.
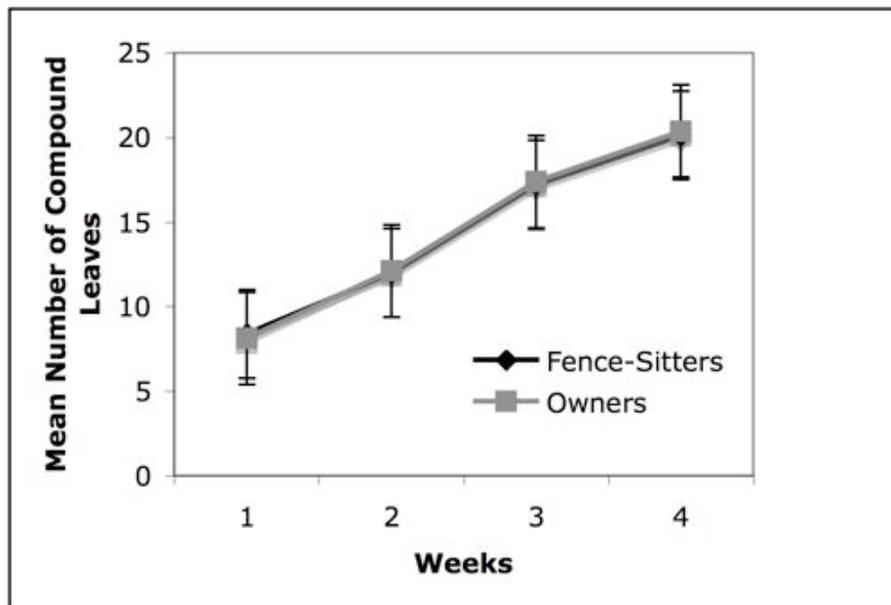
Figure 43. Mean number of compound leaves per sample in weekly measurements for hydroponic fence-sitters versus owners, trial two.
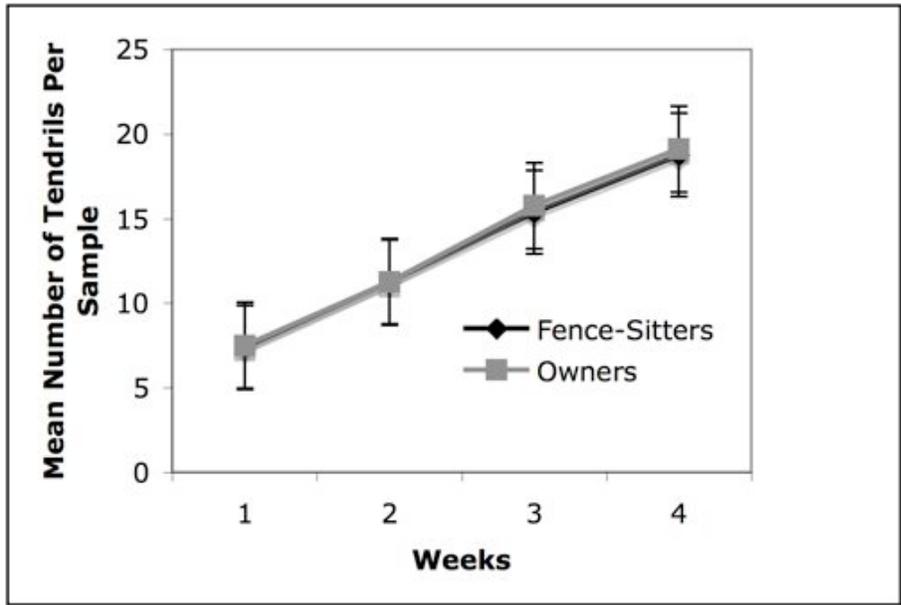
Figure 44. Mean number of tendrils per sample in weekly measurements for hydroponic fence-sitters versus owners, trial two.

Again, the first flowers formed in the third week in like numbers for both treatments, 0.6 per sample (Figure 45), and increased to similar levels by the fourth week, 0.8 per sample. Compared to the first hydroponic trial, there was a 50% increase in flower numbers at week 3, 0.6 flowers per sample versus 0.4 with trial one; however, flower yield at week 4 was similar for both trials, about 0.8 flowers per sample (Figures 41 & 45). Fruits appeared in the fourth week for fence-sitters and owners (Figure 46) like the first hydroponics attempt (Figure 42); however, the yield was double, 1.3 fruits per sample compared to 0.6 per sample in trial one.

Vermiculite-grown plants from trial two (Figure 35) yielded 2.3 fruits per sample, nearly twice the yield measured for hydroponic-grown plants in trial two that received 1,936 lux, a slightly lower light intensity than irradiated vermiculite plants, 2,153 lux. Even though there was little difference in flower and fruit production between

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hydroponic fence-sitters and owners within trials, fruiting was delayed under hydroponic conditions compared to vermiculite-grown plants (cf. Figures 35, 42, & 46) and yields were suppressed. The improved lighting in trial two appeared to be the reason for increased fruit yield for both treatments with a mean of 1.3 fruits per sample in trial two (Figure 46) compared to 0.6 in trial one (Figure 42). The lower, or perhaps delayed, flower and fruit yield in hydroponic versus vermiculite-grown plants were attributed to slight differences in light conditions and other incubation conditions, such as less consistent nutrient levels imposed by soil-less versus soil-culture techniques. Like greenhouse results, a longer incubation period may show improved reproductive yields that occur at a slower rate than vermiculite-grown plants in the lab.

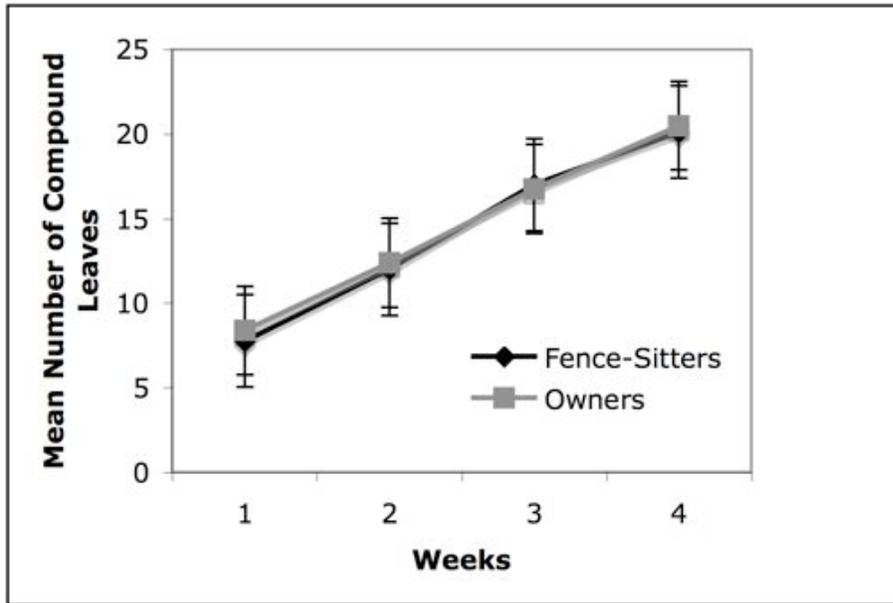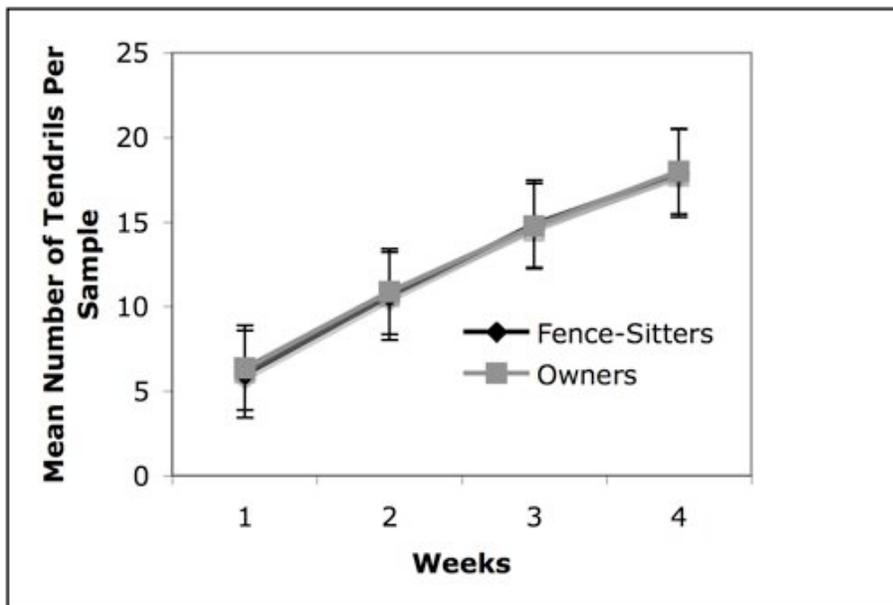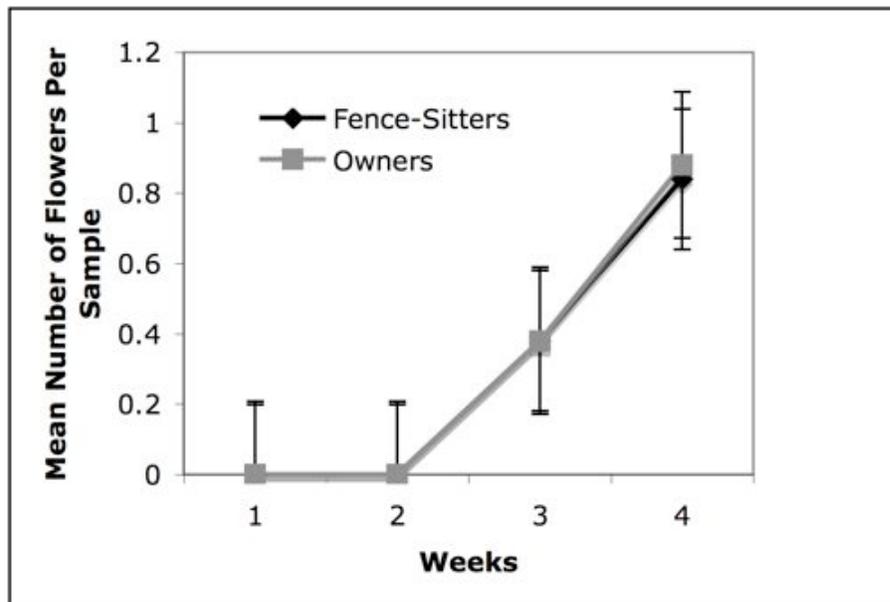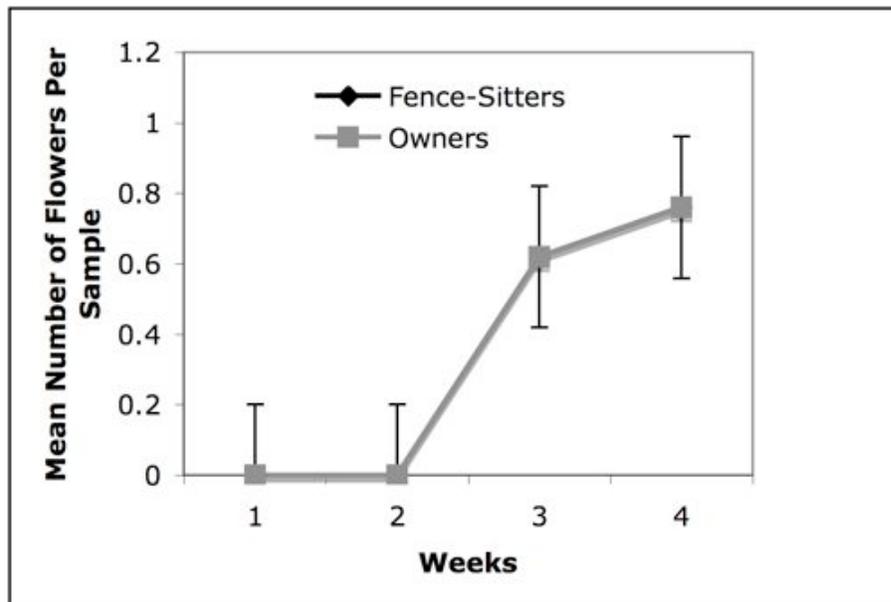*Figure 45*. Mean number of flowers per sample in weekly measurements for hydroponic fence-sitters versus owners, trial two.
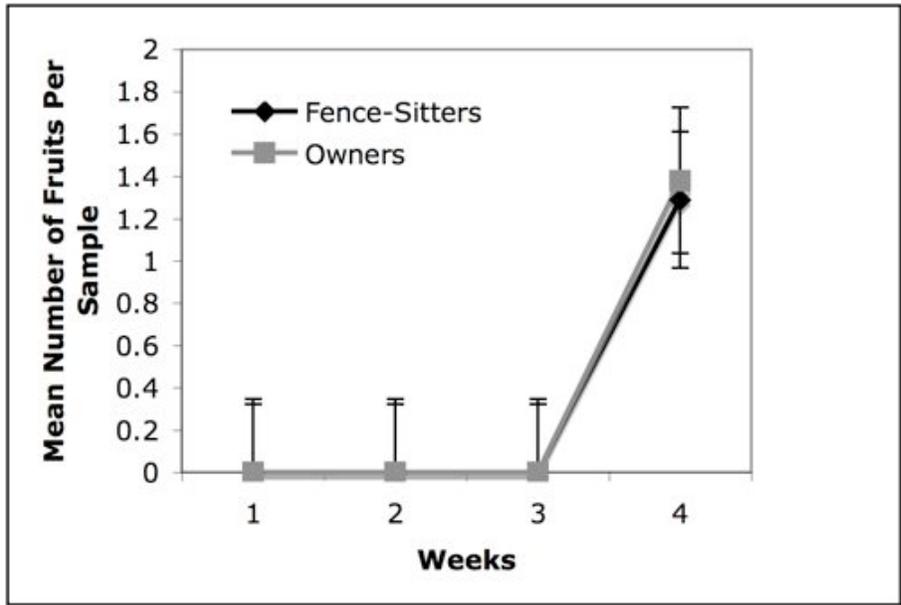
Figure 46. Mean number of fruits per sample in weekly measurements for hydroponic fence-sitters versus owners, trial two.

The general appearance of hydroponic plants from week to week was green, turgid, and healthy with no deaths in trial two. Dry weights were compared for fence-sitters and owners (Table 16) and evaluated statistically using Hotelling's T^2 test yielding $\underline{F}$ (3, 12) = 0.418 with a *p*-value of 0.743254. Consequently, the null hypothesis asserting there was no difference in biomass for the two treatments was not rejected. Root-shoot ratios for fence-sitters and owners were 0.133 and 0.132, respectively (Table 16), further confirming consistent biomass results for the two treatments; however, the root-shoot ratio was smaller than trial one, 0.169 and 0.161 (Table 15), indicating an increase in shoot mass. Besides an increase in shoot mass in trial two, flower/fruit mass increased nine-fold (cf. Tables 15 & 16). Improved lighting in trial two probably accounted for the observed differences. Like trial one and vermiculite-grown fence-sitters and owners, peas

competed through resource matching when growth was analyzed with the habitat

selection model (Table 5).

Table 16

Mean Dry Weights and Standard Errors, p-Value, and Root-Shoot Ratios for Hydroponic Fence-Sitters Versus Owners, Trial Two

	Dry Weights					
	Root (g)		Shoot (g)		Flower/Fruit (g)	
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Fence-Sitters	0.071250	0.006997	0.535875	0.039947	0.193500	0.064066
Owners	0.077250	0.011854	0.584625	0.054601	0.143875	0.028293
p-value = 0.743254						
Root-Shoot Ratios		Fence-Sitters = 0.133		Owners = 0.132		

Note. Sample size = 8, $\overline{X}$ = mean, and SE = standard error.

Fence-Sitters Versus Single-Root Plants. The third experiment, modified from

current literature (Gersani & Sachs, 1992), compared fence-sitters to single-root plants

(Figure 16). The first trial evaluated whether the experiment produced more explicit

results when terminated at 4 or 5 weeks and whether single-root plants proliferated root

mass at a faster rate than fence-sitters when exposed to identical pot space, nutrients, and

water. Unlike previous experiments, one sample was equivalent to one plant, either a

fence-sitter or a single-root plant.

In the first trial, the mean number of compound leaves between fence-sitters and

single-root plants differed in the early weeks (Figure 47). For example, after 1 week of

growth a fence-sitter had at least one more leaf than a single-root plant, and this trend

continued through the second and third weeks. However, by the fourth and fifth weeks the mean number of leaves for the two groups was similar. The same trend was recorded for the tendrils with the mean values differing by at least one tendril per plant in the first 3 weeks, but the gap decreased in the fourth week, and the values were basically identical by the fifth week (Figure 48). In the early weeks, the fence-sitter always had more leaves and tendrils, but it also began with twice the root mass compared to the single-root plant.
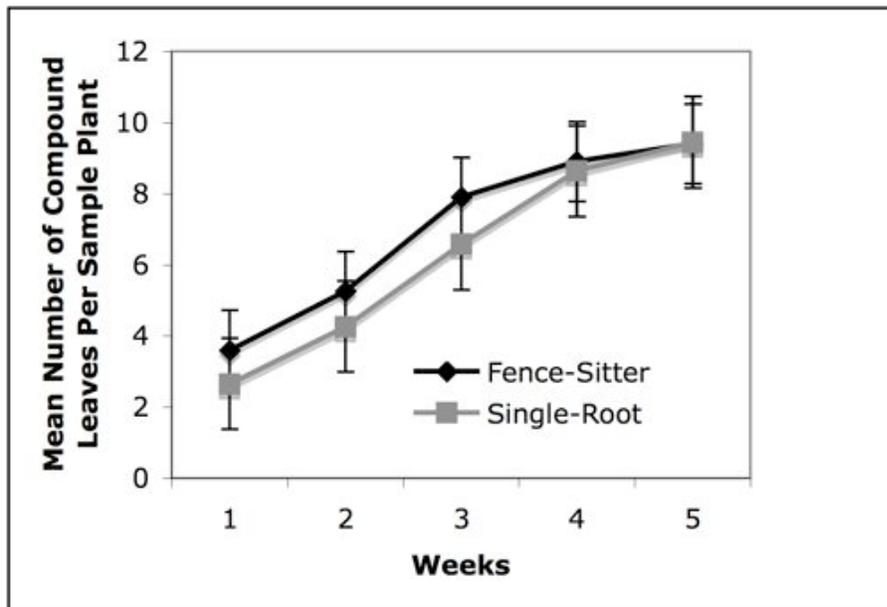
Figure 47. Mean number of compound leaves per sample in weekly measurements for fence-sitter versus single-root plant, trial one.
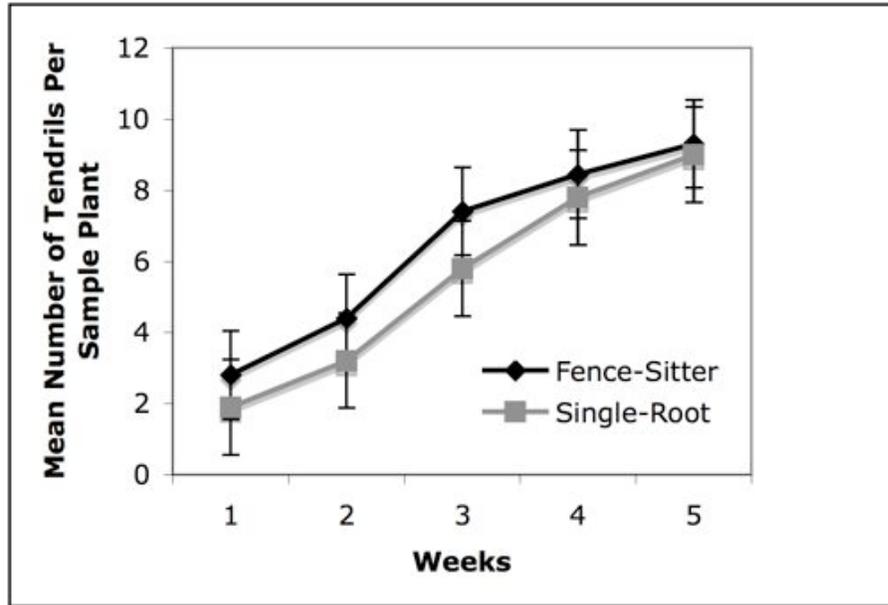
Figure 48. Mean number of tendrils per sample in weekly measurements for fence-sitter versus single-root plant, trial one.

By the third week, the fence-sitters and single-root plants formed flowers, but the fence-sitters had a substantially higher mean number of flowers (Figure 49), 0.65 flowers per plant compared to 0.42 for single-root plants. By the fourth week, the single-root plants peaked in flower number at 0.48 flowers per plants, while the fence-sitters experienced a sharp decline to 0.12 flowers per plant. In the fifth week, fence-sitters lacked flowers and the single-root plants experienced a sharp decline in flower number to 0.12 flowers per plant. Fruit production occurred at different times for the two groups (Figure 50). Fence-sitters initiated pod production by the third week, and the mean number of pods continued to increase in weeks 4 and 5 yielding one pod per plant. Single-root plants did not produce fruit until the fourth week, but nearly matched the number of fruits in fence-sitters by week 5.

It appeared that depending upon initial root mass, the production of flowers and their transition to fruit varied greatly between treatments: fence-sitters flowered in larger numbers earlier in the life span and had an earlier transition to fruit production, while single-root plants formed flowers and fruits more slowly, yet obtained a fruit number similar to fence-sitters by the fifth week. Apparently, the initial smaller root mass of single-root plants caused a delay in the onset of flower and fruit production; perhaps resources used for early reproduction in the fence-sitters were diverted to root proliferation over a greater portion of the life span of the single-root plants. Although fruits occurred in nearly equal number at week 5, the question of whether they attained equivalent maturity was addressed from a different perspective using biomass measurements.
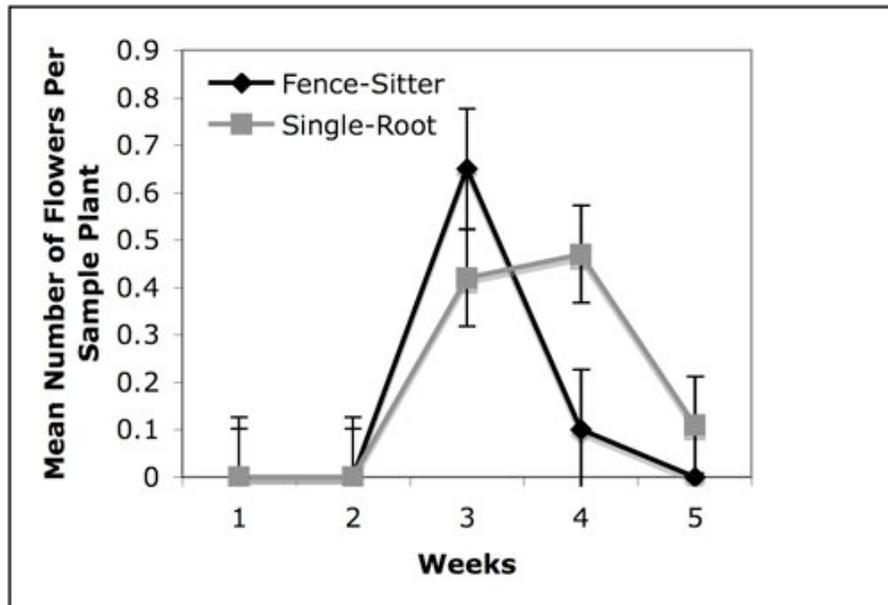
Figure 49. Mean number of flowers per sample in weekly measurements for fence-sitter versus single-root plant, trial one.

Figure 50. Mean number of fruits per sample in weekly measurements for fence-sitter versus single-root plant, trial one.

In terms of overall appearance, each plant was green and healthy except for a single-root plant that died the second week. Symptoms of death for the lone, single-root plant included massive yellowing of new leaves followed by necrosis of all above-ground tissue. While most plants from both treatments were green, wilting was often visible as well as a dryness of the vermiculite indicating the amount of water was insufficient.

Half of the sample units were randomly harvested, dried, and weighed during the fourth week with the remainder, minus the dead single-root plant, processed in the fifth week (Table 17). The sample size was 10 units in week 4 and 9 units in week 5. Mean dry weights for fence-sitters and single-root plants sampled at weeks 4 and 5 were similar for root and shoot biomass (Table 17). Fruit weights, however, were quite different (Table 17). At 4 weeks, fruits of fence-sitters averaged 0.091 g while single-root plants

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averaged 0.022 g. Differences in fruit weights persisted at 5 weeks with fence-sitters averaging 0.168 g and single-root plants 0.095 g.

Table 17

Mean Dry Weights and Standard Errors for Fence-Sitter Versus Single-Root Plant, Trial One

	Dry Weights					
	Root (g)		Shoot (g)		Flower/Fruit (g)	
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Week 4						
Fence-Sitter	0.050800	0.004361	0.231000	0.013762	0.091200	0.012818
Single-Root	0.052400	0.004908	0.211700	0.014773	0.021700	0.007584
Week 5						
Fence-Sitter	0.071300	0.011904	0.227300	0.020214	0.167700	0.023200
Single-Root	0.068667	0.004879	0.19844	0.011386	0.095333	0.012796

Note. Sample size for Week 4 = 10 and sample size for Week 5 = 9, $\overline{X}$ = mean, and SE = standard error.

To determine if there was a statistical difference between total dry weights for the two treatments, the Hotelling's T^2 test was employed for 4- and 5-week data (Table 18). In both cases, *p*-values were less than 0.05 (Table 18) confirming there was a significant difference in the biomass for fence-sitters and single-root plants. The null hypothesis, which asserted no difference in biomass between treatments, was rejected.

Because of the large difference in the fruit mean values (Table 17), the Hotelling's T^2 test was applied to combined root and shoot biomass for the two treatments (Table 18). For the fourth and fifth weeks, the *p*-values were 0.251877 and 0.518420, respectively (Table 18); thus at an alpha value of 0.05, root and shoot biomass was similar between treatments. By deductive reasoning, it was flower/fruit mass that

accounted for differences in total biomass. Root-shoot ratios for fence-sitters and single-root plants were similar for each week (Table 19), mirroring prior conclusions about the similarity of dry weight data and p-values for vegetative biomass. Although root mass for fence-sitters and single-root plants were similar at weeks 4 and 5, the single-root plant proliferated roots at a faster rate during the first 3 weeks of incubation, increasing its root mass from half at time zero to equivalent at week 4. Allocation of resources for root proliferation seemed to delay reproduction in single-root plants and accounted for the smaller reproductive biomass in single-root plants.

Table 18

Hotelling's T^2 Test Values for Dry Weight in Fence-Sitter Versus Single-Root Plant, Trial One

	Hotelling's T^2 Test Values			
	df1	df2	F	*p*
Week 4				
Roots, Shoots, & Fruits	3	16	8.479	0.00136*
Roots & Shoots	2	17	1.497	0.251877
Week 5				
Roots, Shoots, & Fruits	3	15	3.737	0.034252*
Roots & Shoots	2	16	0.685	0.518420

Note. Sample size for week 4 = 10 and sample size for week 5 = 9, df = degrees of freedom, F = test statistic, and p = p-value, * = significant difference.

Table 19

Root-Shoot Ratios for Fence-Sitter Versus Single-Root Plant, Trial One

| | Root-Shoot Ratios | |
	Fence-Sitters	Owners
Week 4	0.220	0.248
Week 5	0.314	0.346

The fence-sitters initially had a larger root mass and total biomass, but by the fourth week, the single-root plants made up the difference, achieving vegetative equivalence and supporting resource matching as the habitat selection preference. The vegetative growth of the single-root plant levels off once it achieved equity with the fence-sitter, probably because nutrient and water availability determined the ceiling for growth rate. Although reproductive biomass was much smaller for single-root plants, these plants may achieve levels measured for fence-sitters given 2 or 3 more weeks for incubation. Reduction to half the root mass appeared to affect the time continuum, which in turn, impacted the competition.

To determine if water and nutrients were a limiting factor, the fence-sitter versus single-root plant experiment was repeated with 60 ml of 0.5 strength Hoagland's medium 3 times a week (Hoagland & Arnon, 1950) instead of 50 ml of 0.25 strength Hoagland's medium 3 times a week used in trial one. The experiment was terminated at 4 weeks of growth, and 20 sample units for each treatment were harvested, dried, and weighed.

In the second trial, fence-sitters had only a slightly larger mean number of compound leaves (Figure 51), amounting to some fraction <1, unlike trial one where variation was >1. Tendrils followed a similar pattern (Figure 52). These vegetative results

differed from trial one where fence-sitters consistently outpaced single-root plants until week 4 (cf. Figures 47, 48, 51, & 52). Because the only differences in experimental conditions between trials was extra water and nutrients applied in trial two, resource availability, more so than reduced root mass, must have accounted for slower leaf development in trial one for single-root plants. Further evidence supporting the conclusion that water and nutrients were limiting in trial one was apparent when the number of compound leaves was compared after 4 weeks of incubation. Trial one fence-sitters and single-root plants averaged 8.5 leaves per plant (Figure 47), while plants from both treatments in trial two averaged 13.5 leaves per plant (Figure 51). The nearly 50% increase in leaf number in trial two must have been related to increased water and nutrients, the only altered variables. It is of interest to note the vermiculite-grown fence-sitters and owners from trial two averaged 20 leaves per sample or 10 leaves per plant at week 4 (Figure 32).
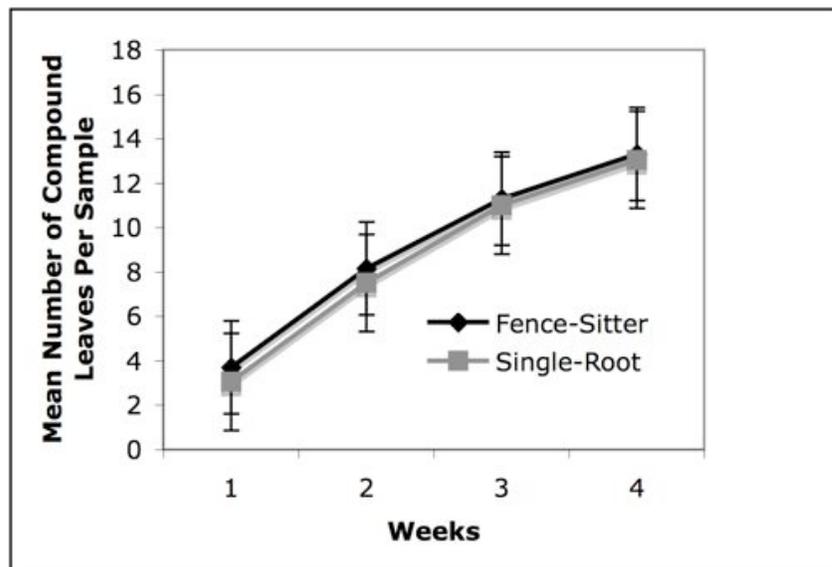
Figure 51. Mean number of compound leaves per sample in weekly measurements for fence-sitter versus single-root plant, trial two.
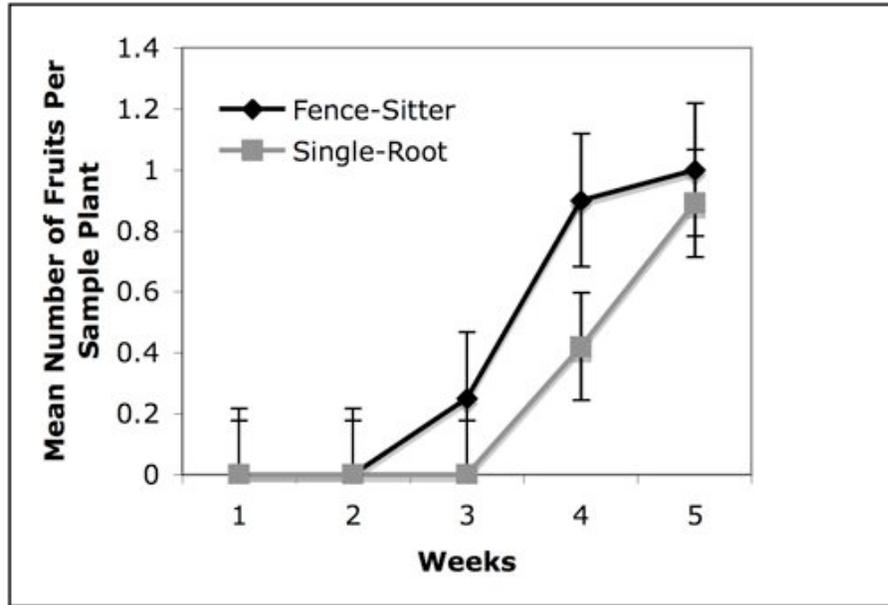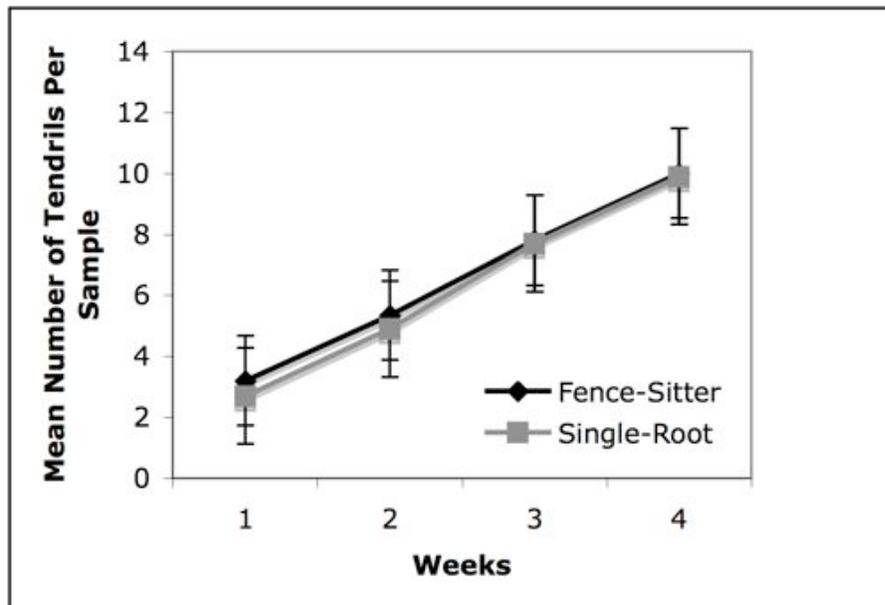
Figure 52. Mean number of tendrils per sample in weekly measurements for fence-sitter versus single-root plant, trial two.

Like trial one, fence-sitters and single-root plants both produced flowers during the third week, but unlike trial one, levels of flower production were consistent between treatments for weeks 3 and 4 (Figure 53). These results were substantially different from the first trial (Figure 49) where single-root plants produced far fewer flowers than fence-sitters in week 3. Differences between trials also were recorded for fruit production. Unlike trial one, fence-sitters delayed fruit formation until week 4 (c.f. Figures 50 & 54), mimicking the timing of fruit production for single-root plants in both trials. Fence-sitters yielded about 0.8 pods per plant at week 4 in trial two and 0.9 in trial one. Single-root plants initiated fruiting during week 4 in both trials (Figures 50 & 54) and produced about 0.75 pods per plant in trial two and 0.45 pods in trial one, nearly half the output. Increased water and nutrients in trial two seemed to decrease variations in fruit yields

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detected in trial one between treatments; however, they did not account for the 1-week

delay in pod formation reported for fence-sitters in trial two. Increased water and

nutrients substantially ameliorated the depressed growth rate experienced by single-root

plants in trial one, permitting the plant with smaller root mass to nearly keep pace with

fence-sitters with twice the root mass.
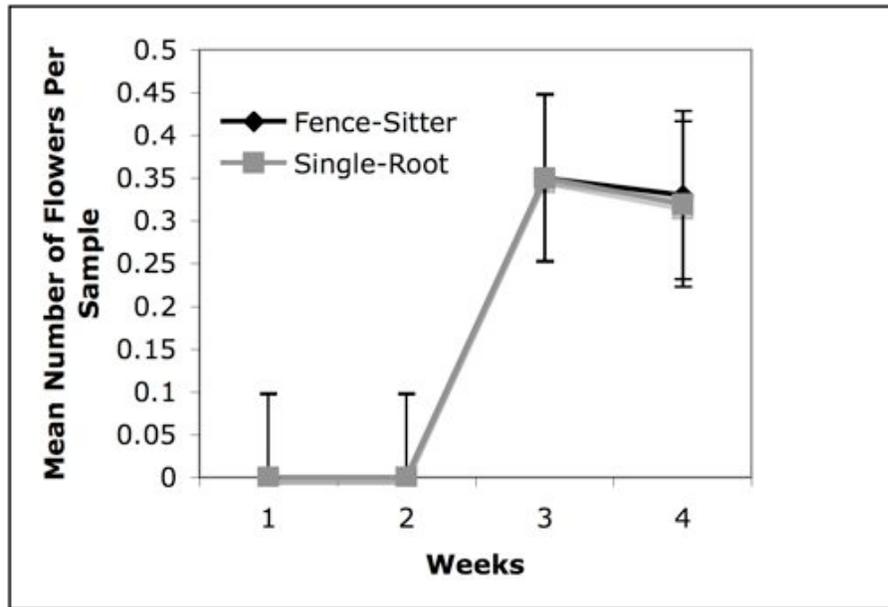
Figure 53. Mean number of flowers per sample in weekly measurements for fence-sitter
versus single-root plant, trial two.
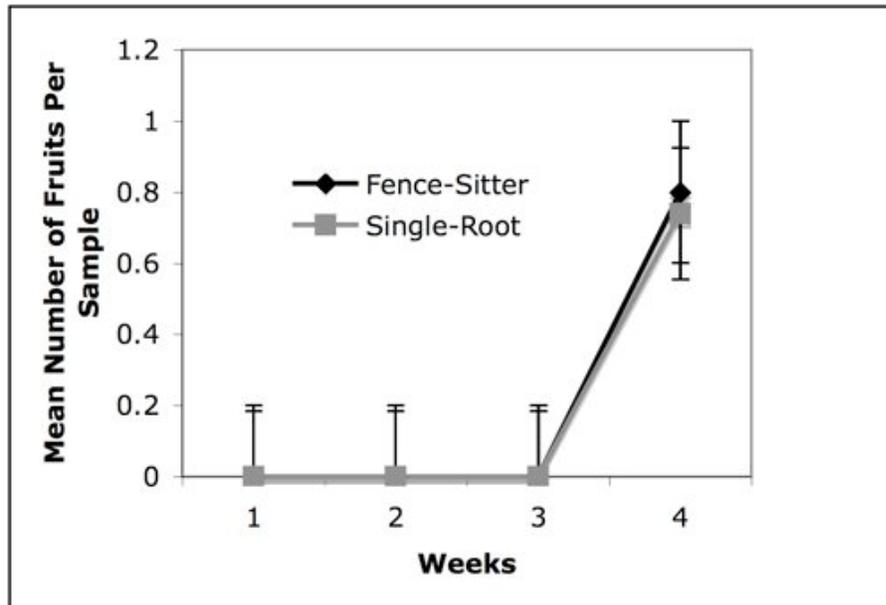
Figure 54. Mean number of fruits per sample in weekly measurements for fence-sitter versus single-root plant, trial two.

Biomass measured as dry weight was compared for fence-sitters and single-root plants using Hotelling's T^2 test and yielded $\underline{F}$ (3, 26) =1.222 with a corresponding *p*-value of 0.315759 (Table 20). The *p*-value was larger than the set alpha value of 0.05; thus, there was no statistical difference in biomass at week 4 between treatments in trial two. Root-shoot ratios were similar for fence-sitters, 0.147, and single-root plants, 0.137 (Table 20), but were much smaller than 4-week ratios in trial one, 0.22 and 0.25, respectively (Table 18). Extra water and nutrients favored a larger shoot mass. Even though the single-root plants initially started with half the root mass of fence-sitters, over the course of 4 weeks, single-root plants produced an equivalent root mass by week 4 (Table 20), generating root mass at a faster rate than fence-sitters. Fruit mass lagged behind slightly in single-root plants (Table 20), indicating that the extra root growth consumed resources reserved for fruit production by the fence-sitters. Besides

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illuminating strategies for resource allocation, this comparison of fence-sitters and single-root plants once again established that peas were responding to resource matching within the root habitat selection model.

Table 20

Mean Dry Weights and Standard Errors, p-Value, and Root-Shoot Ratios for Fence-Sitter Versus Single-Root Plant, Trial Two

	Dry Weights					
	Root (g)		Shoot (g)		Flower/Fruit (g)	
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Fence-Sitter	0.051950	0.002726	0.353100	0.017320	0.080750	0.014529
Single-Root	0.045300	0.002190	0.329650	0.017004	0.060400	0.011447
p-value = 0.315759						
Root-Shoot Ratios		Fence-Sitters = 0.147		Owners = 0.137		

Note. Sample size = 20, $\overline{X}$ = mean, and SE = standard error.

Split-Root Plant Versus Two Single-Root Plants. Another original design compared the above-ground growth and dry weights of a split-root plant versus two single-root plants (Figure 25). Two trials were performed with the first attempt focusing on timing and feasibility of the design. Similar to the first trial of the previous experiment, half of the sample units were harvested at 4 weeks and half at 5 weeks. Measurements for the two single-root plants in one pot were summed and treated as one sample and compared to a single split-root plant occupying one pot and treated as one sample. Although root mass was equivalent at zero time for both treatments, twice the shoot mass was supported in the single-root pot.

In the first trial, the mean values of leaves and tendrils for the two combined single-root plants remained approximately twice that of split-root plants throughout the 5-week period (Figures 55 & 56). All shoots added leaves and tendrils at the same rate, regardless of pot placement or competition, retaining the initial 2:1 relationship between treatments.
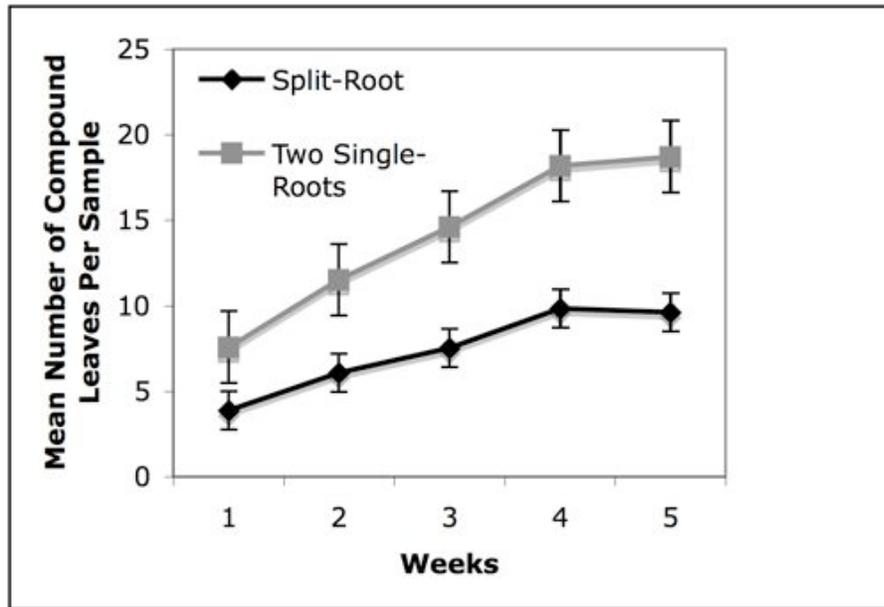
Figure 55. Mean number of compound leaves per sample in weekly measurements for split-root plant versus two single-root plants, trial one.
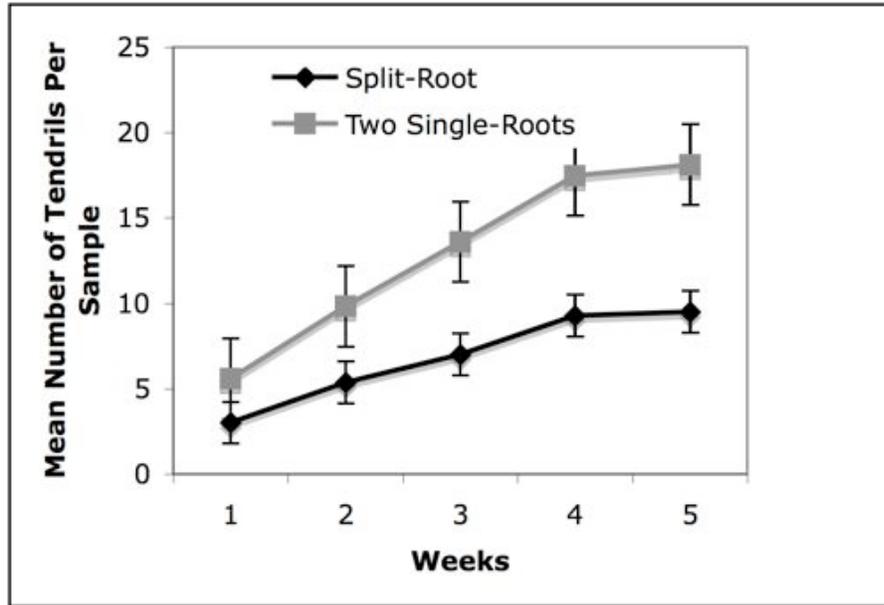
Figure 56. Mean number of tendrils per sample in weekly measurements for split-root plant versus two single-root plants, trial one.

During the third week, the two single-root plants and split-root plant initiated

flowering and increased in flower number during the fourth week (Figure 57), repeating

the consistent 2:1 ratio recorded for leaves and tendrils (Figures 55 & 56). By the fifth

week, the mean number of flowers declined sharply for both groups. Fruit production

occurred for both groups in the fourth week, again in a 2:1 ratio (Figure 58). Regardless

of treatment, the timing of reproduction was simultaneous, and equivalent numbers of

flowers and fruits were produced per plant (Figures 57 & 58).

Figure 57. Mean number of flowers per sample in weekly measurements for split-root plant versus two single-root plants, trial one.

Figure 58. Mean number of fruits per sample in weekly measurements for split-root plant versus two single-root plants, trial one.

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Wilting and yellowing of leaves were observed more often for the two single-root plants, while the split-root plants remained green, turgid and healthy. Nutrients and water were probably limiting for the single-root treatment; thus, both were increased in trial two.

Dry weight biomass for roots and fruits were similar between the treatments in weeks four and five (Table 21) yielding approximately a 1.25:1 ratio for single-root pair compared to the single split-root plant. At time zero, the rates for root biomass was 2:1, so the split-root plant made significant gains in root mass in a 4-week period. Summed shoot mass for the pair of single-root plants exceeded that of the single split-root plant by 1.25:1 in week 4 and 1.80:1 in week 5 (Table 21). While leaf and tendril numbers retained the 2:1 ratio throughout the 5-week period, shoot biomass data revealed a different outcome. The split-root plant gained shoot biomass by week 4 without changing the rate of leaf formation; however, gains in shoot mass were lost during week 5 and were, perhaps, diverted to fruit production.

Table 21

Mean Dry Weights and Standard Errors for Split-Root Plant Versus Two Single-Root Plants, Trial One

	Dry Weights					
	Root (g)		Shoot (g)		Flower/Fruit (g)	
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Week 4						
Split-Root	0.112333	0.013556	0.424667	0.050752	0.067444	0.020528
Two Single-Roots	0.140875	0.006932	0.541125	0.054171	0.091375	0.015720
Week 5						
Split-Root	0.131875	0.020364	0.271000	0.023767	0.232750	0.027255
Two Single-Roots	0.166557	0.008431	0.488667	0.029839	0.285000	0.024051

Note. Sample size for Week 4 = 9 and Week 5 = 8. $\overline{X}$ = mean, and SE = standard error.

To determine whether there was a significant difference between biomass for the two groups, Hotelling's T^2 test was applied and yielded $\underline{F}$ (3, 13) = 2.171 with a corresponding *p*-value of 0.140402 for week 4. Because the *p*-value was greater than the set alpha value of 0.05, there was no significant difference in biomass between the two treatments in week 4 (Table 22). For the fifth week, the Hotelling's T^2 test produced $\underline{F}$ (3, 13) = 36.739 with a *p*-value of 0.000841 (Table 22), indicating there was a significant difference in total biomass. The Hotelling's T^2 test was performed again, comparing the root and fruit mass for week 5 and yielding $\underline{F}$ (2, 14) = 1.494 with a *p*-value of 0.258099 (Table 22). Thus, root and fruit biomass were not significantly different, but by deductive reasoning, it was shoot mass that differed in week 5.

Table 22

Hotelling's T^2 Test Values for Dry Weights in Split-Root Plant Versus Two Single-Root Plants, Trial One

	Hotelling's T^2 Test Values			
	df1	df2	F	*p*
Week 4				
Roots, Shoots, & Fruits	3	13	2.171	0.140402
Week 5				
Roots, Shoots, & Fruits	3	13	36.739	0.000841*
Roots & Fruits	2	14	1.494	0.258099

Note. df = degrees of freedom, F = test statistic, *p* = *p*-value, * = significant difference.

The root-shoot ratios were similar for the split-root plant and two single-root plants in week 4, 0.265 and 0.260, respectively, but differed in the fifth week, 0.487 and 0.341 (Table 23). As documented in the distribution of dry weight biomass (Table 21), shoot mass but not leaf number was produced at a faster rate in the split-root plant during the first 4 weeks; however, during week 5 the production rate for shoot mass declined in both treatments, but shoot loss sustained by the split-root plant was much greater as evidenced by the larger root-shoot ratio (Table 23). Initially, shoot mass changed in an attempt, perhaps, to match resources; thus, there were greater gains in shoot mass for the split-root plant. However, the onset of reproduction seemed to induce shoot loss in favor of gains in reproductive mass. This experiment comparing the effects of half the shoot mass, but equivalent root mass had a different outcome than the previous experiment that compared half of the root mass but equivalent shoot mass. In both instances, the deficient plant organ grew at a faster rate based on biomass gains, but plants deficient in shoot

mass experienced a set-back during the reproductive phase not recorded for plants with deficient root mass. Apparently, conversion of vegetative shoot tissue to reproductive tissue exacted a greater toll when the initial deficiency was shoot mass. Perhaps, continuation of the experiment for another week or two may have shown whether excess fruit mass was produced by the shoot deficient, split-root group. Otherwise, an inefficiency in the maturation process proceeding from the vegetative to the reproductive phase must be assumed.

Table 23

Root-Shoot Ratios for Split-Root Versus Two Single-Root Plants, Trial One

| | Root-Shoot Ratios | |
	Split-Root	Two Single-Root
Week 4	0.265	0.260
Week 5	0.487	0.341

The first trial of the split-root plant versus two single-root plants proved the design was feasible, but a second 4-week trial was designed with an increase in sample size from 9 to 20 and an increase from 40 ml of 0.25 strength Hoagland's medium (Hoagland & Arnon, 1950) to 50 ml of 0.5 strength. Increasing the concentration and quantity of nutrients and water was designed to combat wilting and yellowing of leaves noted in the first trial.

In trial two, the mean values for compound leaves and tendrils for the two single-root plants in one pot were basically twice the values for the single split-root plant; however, the interval widened to 2.5:1 in the later weeks (Figures 59 & 60), unlike the 2:1 ratio in trial one (Figures 55 & 56). Likewise, the leaf and tendril yield at week 4 was

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greater in both treatments compared to trial one and probably was a result of increased

water and nutrients in trial two. The combined single-root plants produce 25 leaves by

week 4 in trial two (Figure 59), but only 19 leaves were counted in trial one (Figure 55).

The split-root plant produced 13 leaves in trial two (Figure 59) and 8 leaves in trial one

(Figure 55). Apparently, growth was limited by water and nutrient availability in trial

one.
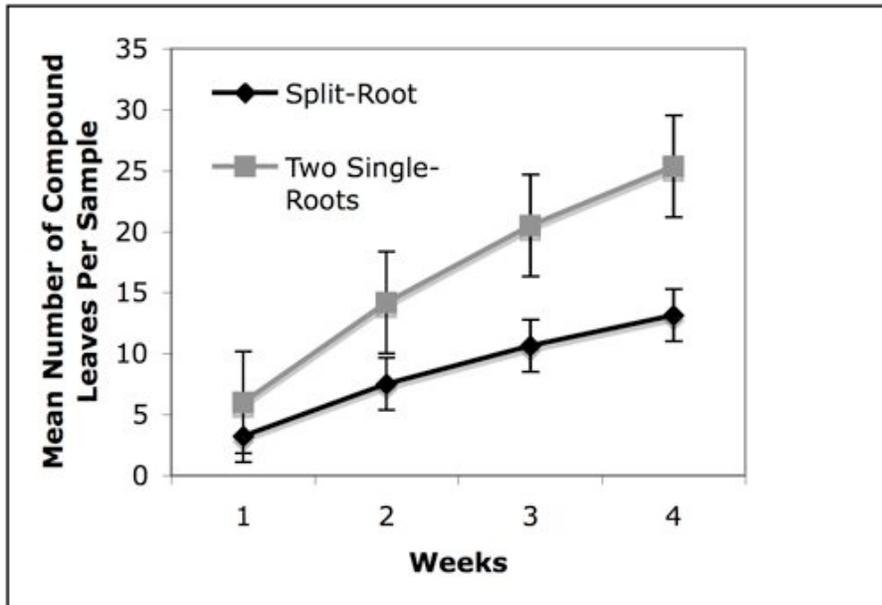
Figure 59. Mean number of compound leaves per sample in weekly measurements for split-root plant versus two single-root plants, trial two.
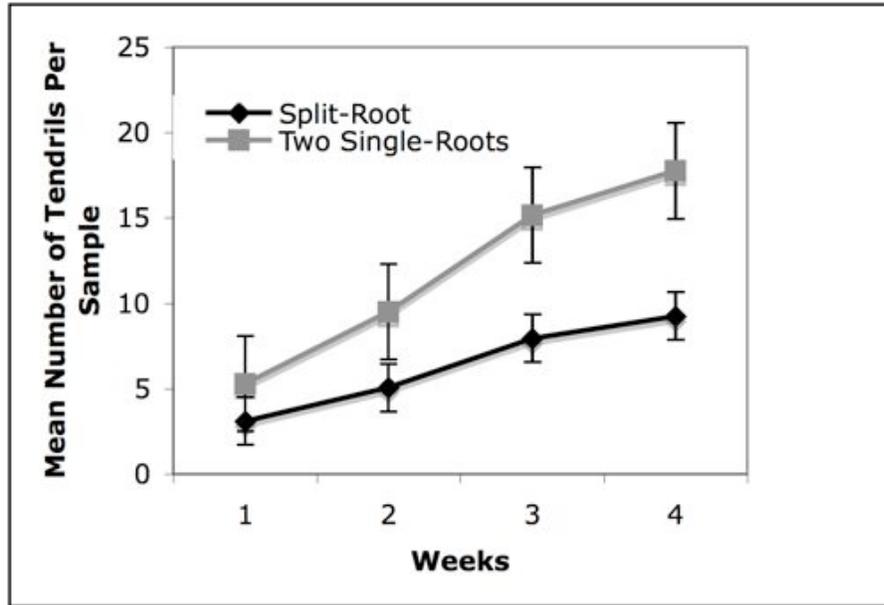
Figure 60. Mean number of tendrils per sample in weekly measurements for split-root plant versus two single-root plants, trial two.

While both groups initiated flowering in the third week, the pair of single-root plants had nearly twice the flower number as the split-root plant by week 4 (Figure 61). A similar observation was made for week 4 in trial one (Figure 57). Fruit production occurred in the fourth week for both treatments (Figure 62), demonstrating a 2:1 fruit ratio. Increased nutrients and water improved fruit production in split-root plants and single-root plants compared to trial one (Figure 58). Split-root means for fruits improved from 0.45 per sample in trial one to 0.6 in trial two, while pairs of single-root plants increased fruit production from 0.95 fruits per sample in trial one to 1.4 in trial two.
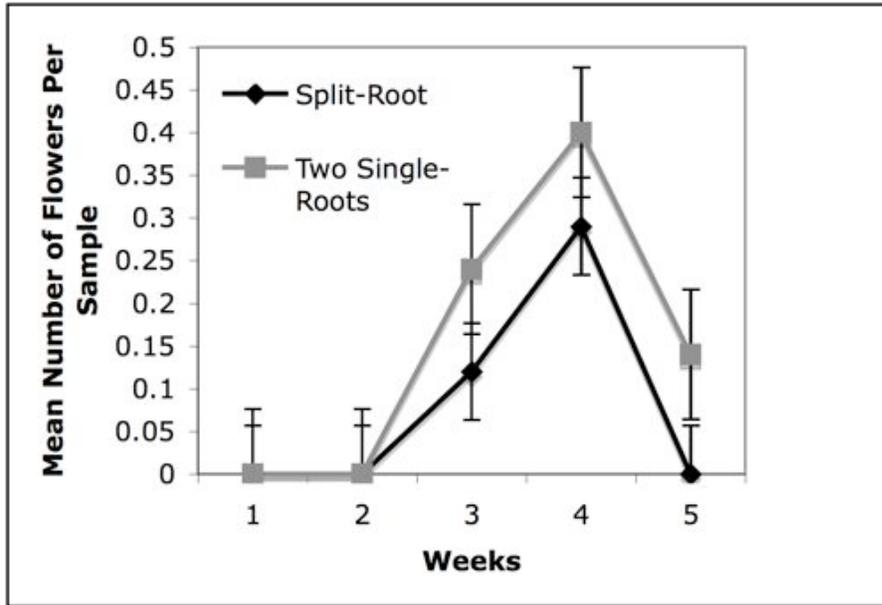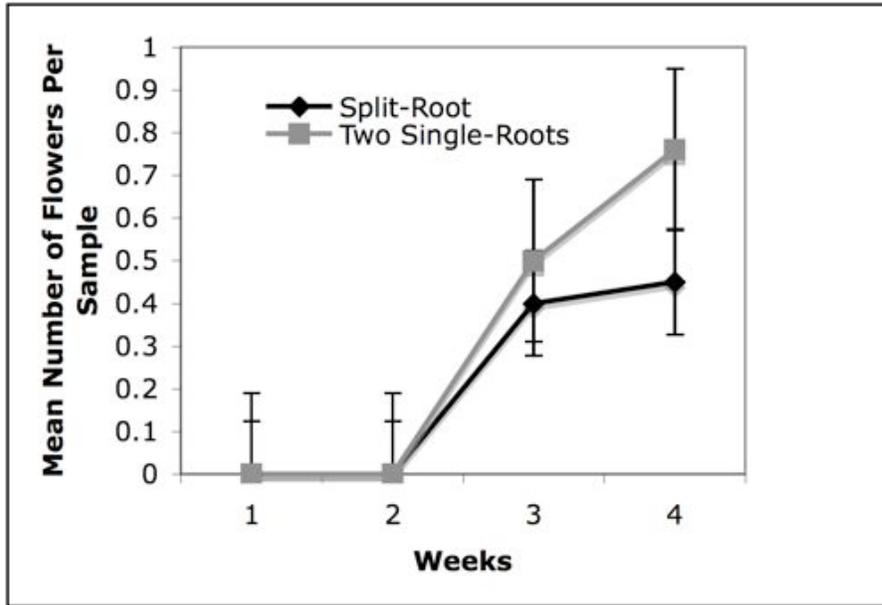
Figure 61. Mean number of flowers per sample in weekly measurements for split-root plant versus two single-root plants, trial two.

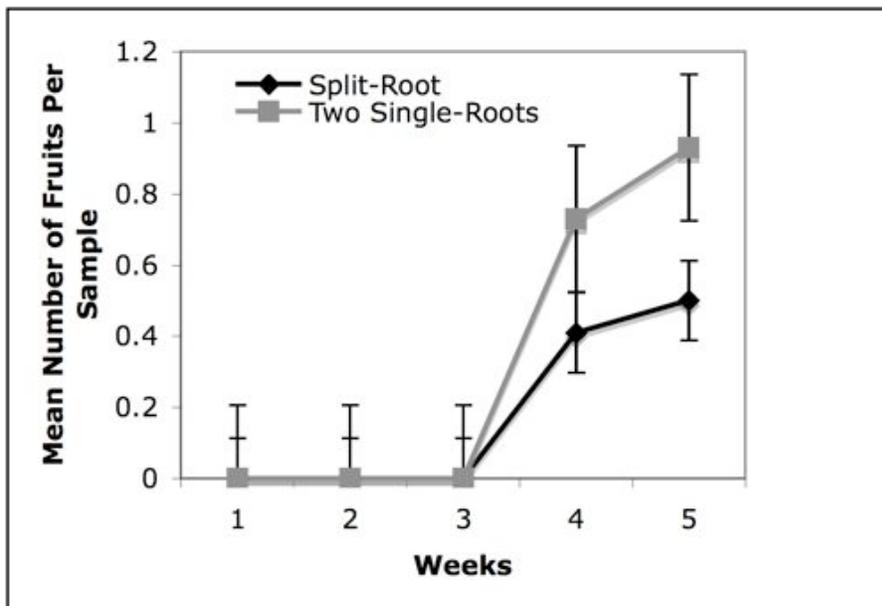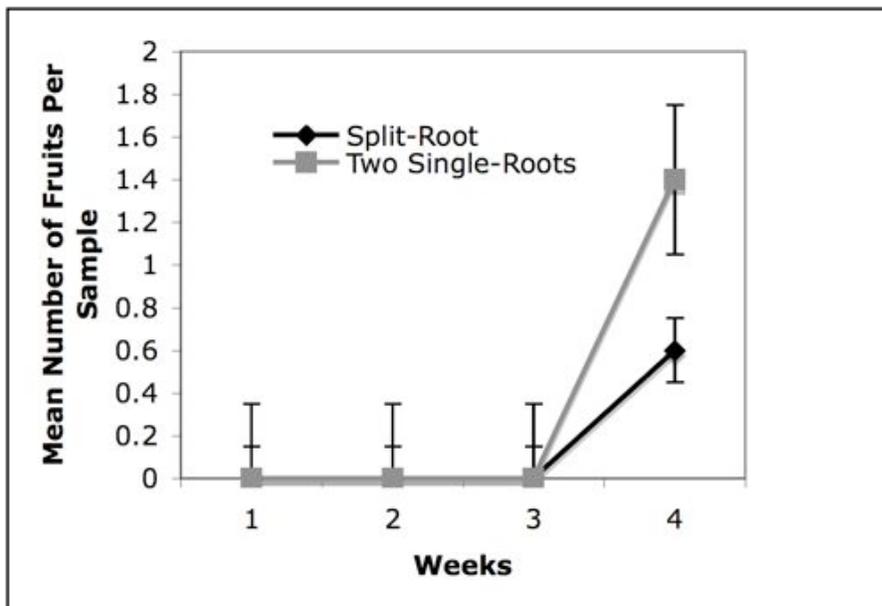*Figure 62*. Mean number of fruits per sample in weekly measurements for split-root plant versus two single-root plants, trial two.

The plants were green and healthy with little wilting and no yellowing of leaves over the 4-week period. The increased nutrient and water seemed to alleviate problems encountered in trial one with wilting and yellowing leaves noted.

After 4 weeks, dry weights for the split-root plant and combined weights for single-root plant pairs were evaluated (Table 23). Like trial one, root and fruit biomass showed about 1.25:1 ratio for single-root plants to the split-root plant, although they started with a 2:1 shoot ratio at time zero (cf. Tables 22 & 24). Shoot biomass, however, had a 1.64:1 ratio for treatments in trial two (Table 24), contrary to the 1.25:1 ratio in trial one at week 4 and the 1.80:1 ratio at week 5 (Table 22). To determine whether the observed differences in biomass were significant required statistical testing.

Table 24

Mean Dry Weights and Standard Errors for Split-Root Plant Versus Two Single-Root Plants, Trial Two

	Dry Weights					
	Root (g)		Shoot (g)		Flower/Fruit (g)	
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Split-Root	0.041300	0.002118	0.291800	0.011477	0.043000	0.009536
Two Single-Roots	0.049150	0.003608	0.480300	0.014866	0.056900	0.009842
Root-Shoot Ratios	Split-Root = 0.142		Single-Roots = 0.102			

Note. Sample size = 20. $\overline{X}$ = mean, and SE = standard error.

The Hotelling's T^2 test yielded F=38.997 with a *p*-value of less than 0.000001; thus, the null hypothesis stating that dry weights were the same was rejected (Table 25). To investigate which dry weights differed, a Hotelling's T^2 test was applied to combined

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root and fruit data, producing a *p*-value of 0.180540 (Table 25) and indicating root and

fruit biomass were similar between groups. By deductive reasoning, shoot biomass was

statistically different for split-root and paired single-root plants. A similar result was

obtained in trial one, but at the fifth, not fourth, week of growth (Table 22). It seemed

that increased nutrients and water permitted a faster rate of shoot growth. Comparison of

root-shoot ratios clearly showed that shoot mass was still lagging behind in split-root pots

(Table 24) with the split-root sample yielding a ratio of 0.142 and the single-root sample

0.102.

Table 25

Hotelling's T^2 Test Values for Dry Weight in Split-Root Plant Versus Two Single-Root Plants, Trial Two

	Hotelling's T^2 Test Values			
	df1	df2	F	*p*
Roots, Shoots, & Fruits	3	36	38.997	<0.000001*
Roots & Fruits	2	37	1.794	0.180540

Note. Df = degrees of freedom, F = test statistic, and *p* = *p*-value, and * = statistically different.

Where root mass was concerned, both treatments in trial one and two probably

exhibited the resource matching response within the root habitat selection model. The

equivalent root mass of the two treatments seemed to support nearly equivalent fruit

mass. The two single-root plants had a larger shoot mass than the split-root plant, which

was not surprising since the two single-root plants started with twice the root mass;

however, the interval for differences in shoot mass between treatments was lowered from

2:1 to 1.64:1. Apparently, the split-root plant was unable or had no need to attain

equivalent shoot mass with the single-root pair prior to reproductive maturation.

Two Fence-Sitters Sharing a Space. The third original design involved two fence

sitters with half of their root mass occupying a large, shared pot and half in a smaller,

dedicated pot (Figure 26). Unlike other designs, the shoots cannot be compared because

the only treatment difference lied in the placement of the roots. In the first trial with a

sample size of 10 units, the root dry weights were compared after 4 weeks of growth. The

root weights for the two small pots were combined as were the two roots occupying the

larger pot (Tables 26). Using the paired *t*-test, the first trial yielded t = 0.60 with a *p*-value

of 0.566347 for a sample size of 10, while in trial two with a sample size of 20, the paired

t-test yielded *t* = 0.15 with a *p*-value of 0.882163 (Table 27). Consequently, there was no

significant difference in root mass for either trial when the preset alpha value was 0.05,

and the null hypothesis was not rejected. Apparently, peas formed identical root mass

whether in isolation or intra-species competition, provided identical space and resources

were available. When root mass was equivalent whether growing in isolation or in

competition, then resource matching explained root competition according to the root

habitat selection model.

Table 26

*Mean Root Dry Weights and Standard Errors and p-Value for Two Fence-Sitters
Simultaneously Sharing and Not Sharing a Space, Trial One*

	Root Dry Weights (g)	
	$\overline{X}$	SE
Two Roots in Large Pot	0.101700	0.010991
Two Roots in Two Small Pots	0.105100	0.009236
p-value = 0.566347		

Note. Sample size = 10, $\overline{X}$ = mean, and SE = standard error.

Table 27

Mean Root Dry Weights and Standard Errors and p-Value for Two Fence-Sitters Simultaneously Sharing and Not Sharing a Space, Trial Two

	Root Dry Weights (g)	
	$\overline{X}$	SE
Two Roots in Large Pot	0.091550	0.003321
Two Roots in Two Small Pots	0.091000	0.003272
p-value = 0.882163		

Note. Sample size = 20, $\overline{X}$ = mean, and SE = standard error.

Each of these five experimental designs investigated an aspect of root competition. Researching several adapted and original designs was necessary not only to make certain recent research could be modified for the classroom, but to ascertain whether classroom equipment, supplies, and facilities were adequate. Also, other possible problems likely to be encountered by students were tackled and overcome. The next step was to develop an appropriate instructional plan to ensure a successful learning experience that meets the original goals of motivating students, providing students opportunities for critical and creative thinking, and experience with statistical analysis, technology, and communication of findings.

Instructional Design

The instructional plan was based on the ADDIE Model (Analyze, Design, Develop, Implement, and Evaluate). Each stage had specific objectives essential for effective instruction.

Analyze

Analysis was performed in two steps, determining the knowledge base and skills of the learner and defining learning objectives. Students participating in the two field trials were enrolled in Medicinal Botany (objectivist-teaching strategy) or Plant Physiology (constructivist-teaching strategy). Both were upper division courses, and General Botany was a prerequisite; thus, enrolled students were familiar with a wide range of plant concepts at the introductory level, including plant anatomy and development, organ function, and plant propagation. Students had completed 6-8 college laboratory courses, and had developed some skill with maintaining living organisms, data collection, and the scientific method.

Learning objectives included three crucial characteristics, condition, performance, and criteria. Root competition studies had the overall purpose of providing experience with research, critical thinking, experimental design and analysis, and scholarship. After the instructor presented background knowledge on root anatomy, function, and competition, the recent scientific literature and habitat selection models for root competition were provided as reading and discussion materials. A well-designed experiment was dissected and examined (condition), then students were asked to design, execute, and analyze their own root competition experiment (performance). The experimental design developed by students must have supported a null and alternative hypotheses related to root competition and employed the appropriate statistical test (criteria). Students were responsible for making careful plant observations and measurements and analyzing and interpreting all data.

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Students learned how to manipulate plants to form split-roots, plant culture methods, data collection techniques, and applications for statistical analysis. Experimental design required critical thinking and application of the scientific method. Because original experiments were designed by students, participation in scholarship or the process of adding new scientific knowledge was experienced, and communication skills were honed during class discussions and oral and written reports.

Design

Design considerations included selection of instructional and motivational strategies as well as student assessment. Instructional strategies were implemented in two steps, creation of instructional aids, such as handouts and an activity schedule, plus protocol for teaching root competition using an objectivist and a constructivist format. The motivational strategies employed were participation, research skills applicable to becoming a professional scientist, positive reinforcement, and original contributions to science. Students gained a sense of accomplishment through active participation and were motivated if the lesson was made relevant to creating new science. By emphasizing knowledge already acquired and establishing a clear plan for expectations, students gained self-confidence, and satisfaction was increased through positive reinforcement that defines the magnitude of their successes.

To determine whether objectives were met, the assessment plan involved students writing a report suitable for publication that matched the primary objective. Additional opportunities for assessment included an oral report and class discussion of the experimental design, results, and analyses to an audience of classmates. Thus, students

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used written and oral communication skills to demonstrate whether criteria were met within the instructional objective and whether skills necessary for a scientific career were strengthened. These assignments were appropriate assessment tools for the objectivist- and constructivist-classrooms.

Develop

Instructional materials, plan for technology use, and schedule for events were developed for the objectivist- and constructivist-classroom. Step-by-step procedures already tested and shown to be reproducible by the instructor were given to objectivist-learners. The handouts for the fence-sitter versus owner experiment utilizing vermiculite included a summary of background knowledge and laboratory protocols (Appendix C). Students were provided with journal articles on root competition as required readings, and the role of the teacher was defined as presenter of knowledge, demonstrator, resource for questions, task master, and qualitative evaluator of student and project success.

As stressed by the ADDIE Model, the project was re-evaluated in all instructional phases. In the objectivist-classroom, the performance portion of the objective did not include an original design, but students were asked to execute and analyze an experiment already tested. The skills already listed, except for ones concerning designing an experiment, fit within the principles of objectivism.

For the constructivist-classroom, handouts provided some background instruction but focused more on the process of experimental design, challenging students in groups to construct an original root competition experiment using previous knowledge and new knowledge gained through reading the scientific literature. The handouts presented the

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fence-sitter versus owner experiment as an example of a good research design and as a starting point for discussion and development of an outline for general procedures (Appendix D) that investigate a new research question. The teacher was responsible for coaching the students as they developed hypotheses, overseeing and guiding each group as tests were performed, and qualitatively evaluating student and project success. The original stated objective and skills aligned with using constructivism as a teaching strategy.

Other handouts were written for both teaching experiences. A guide for writing a lab report outlined the major elements of a science manuscript (abstract, introduction, methods, results, discussion, and references) as well as expected contents for each section (Appendix E). An instructor rubric for grading the lab report was based on the outline prepared for the students (Appendix F). Supplements, including journal articles (such as Maina et al., 2002) and PowerPoint presentations entitled "Habitat Selection Models" and "Experimental Design," were gathered and developed. Also, a class discussion guide with key questions for groups in both the objectivist- and constructivist-classroom was designed (Appendices G & H). Since each objectivist-student performed the same experiment, the class discussion focused on results and interpretation of results. A student evaluation form was created for both classrooms questioning students about perceptions and asking students to apply learning through an application question (Appendices I & J). The forms only differed in one major aspect, the objectivist students were invited to design an original root competition experiment, and the constructivist students were challenged to develop another experimental design.

Another essential part of the instructional plan was the incorporation of technology when appropriate. At each class meeting, students posted data on Excel spreadsheets programmed to calculate means and plot graphs. For both classroom approaches, copies of handouts, results, articles, and grades were posted to a password protected website called eLearning by the University of West Florida and maintained by Desire2Learn (https://elearning.uwf.edu/secure/index.cfm). Students could obtain important information concerning their experiment at any time. For the constructivist-based approach, extra technology was used in the form of online tutorial videos developed by the instructor that presented background and procedural information, useful as a guide for creation of original student research (http://www.uwf.edu/selliott1/). Through videos, students were able to see an example of how to create and handle split-root peas as well as how to place plants in a variety of pot arrangements. Interactive Flash quizzes enabled students to self-test their understanding of the content and provided immediate feedback. It is evident that the technology quizzes provided a valuable, self-testing tool for students.

The teaching schedule for both field trials varied mostly in the initial weeks (Table 28) mainly because the constructivist class required extra time for creating an original experimental design. However, both teaching strategies had students perform the split-root technique and take qualitative and quantitative plant measurements over a 4-week period that were subsequently evaluated through statistical analysis. The final week was devoted to interpretation of results, student or group oral presentations, and project evaluation.

Table 28

Plan for Student Responsibilities in the Two Teaching Paradigms

| | Objectivist | Constructivist |
	Student Responsibilities	Group Responsibilities
Week 1	Plant seeds in ragdolls; read journal articles	Plant seeds in ragdolls; form groups; discuss options for experimental design
Week 2	Cut root tips	Cut root tips; discuss design
Week 3	Make and pot split-roots	Decide on experimental design; make and pot split-root plants
Week 4	Qualitative and quantitative measurements	Qualitative and quantitative measurements
Week 5	Qualitative and quantitative measurements	Qualitative and quantitative measurements
Week 6	Qualitative and quantitative measurements	Qualitative and quantitative measurements
Week 7	Qualitative and quantitative measurements; harvest plants	Qualitative and quantitative measurements; harvest plants
Week 8	Dry weight measurements and statistical analysis	Dry weight measurements and statistical analysis
Week 9	Oral report and discuss data; evaluation	Oral report and discuss data; evaluation
Week 10	Written report due	Written report due

Implement

Objectivist-based and constructivist-based field trials constituted the implementation stage. Because of the lack of repetition, each field trial was not statistically valid but provided certain qualitative insights and observations. Time constraints dictated the organization of the field trials. In the objectivist-teaching experience, students did not design an experiment but started by manipulating root development to form split-root plants, took plant measurements for three weeks, and

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finished with statistical analysis and discussion of data in the last week. For the

constructivist-based trial, extra time was set aside for creating an original experimental

design during the initiation phase; otherwise, the implemented schedule was identical

(Table 29).

Table 29

Implemented Plan for Student Responsibilities in the Two Teaching Paradigms

	Objectivist Student Responsibilities	Constructivist Group Responsibilities
Week 1	Teacher plants seeds and cuts distal root tips; student makes and pots split-roots	Plant seeds in ragdolls; form groups; discuss options for experimental design
Week 2	School Break	Cut root tips and discuss design
Week 3	Qualitative and quantitative measurements	Decide on experimental design; make and pot split-root plants
Week 4	Qualitative and quantitative measurements	Qualitative and quantitative measurements
Week 5	Qualitative and quantitative measurements; harvest plants	Qualitative and quantitative measurements
Week 6	Dry weight measurements and statistical analysis	Qualitative and quantitative measurements
Week 7	Oral report and discuss data; evaluation	Qualitative and quantitative measurements; harvest plants
Week 8		Dry weight measurements (teacher); Student statistical analysis, oral report, and data discussion; evaluation
Later	Written report due	Written report due

Evaluate

Evaluation occurred at every step of the instructional design process; however, it was crucial following implementation. Data from various sources, such as fieldnotes, lab reports, and student evaluations, were collected and reviewed to determine learning outcomes and whether student scientific data concurred with instructor results. While each field trial was insufficient for statistical analysis, teacher insights identified problems that required revision.

Field Trials and Observations

Field trials were an essential component of the implement stage. Each trial was run and analyzed separately and data collection consisted of fieldnotes, documents, and student evaluations.

Objectivist-Teaching Trial

The five students in the objectivist-based field trial individually performed the fence-sitter versus owner experiment. As documented in the fieldnotes and student evaluations (Appendices K & L), students worked individually and prefered to work individually; directed questions to the instructor, not fellow classmates; and perceived the teacher as an authoritative figure. For each student experiment, the number of leaves, tendrils, flowers, and fruits for the two treatments was similar, and all split-root plants survived. In addition, statistical analysis of dry weights using the Hotelling's T^2 test for all student experiments yielded a p-value larger than the set alpha value of 0.05, ranging from 0.2 to 0.6; thus, the null hypothesis for each student experiment was not rejected.

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Because the results concurred with instructor trials and the scientific literature, the experimental design was valid and a scientific success.

Whether the criteria for the primary objective of the lesson were met was judged through the class discussion and lab reports. During the class discussion, each student presented his/her results concisely with logical interpretation. In addition, each student produced a manuscript written in scientific style that correctly addressed each topic in the lab report guidelines, thus, illustrating an understanding of basic concepts that explained root competition, methods and skills required for the experiment, data collection, computation, interpretation and analysis, and determination of the appropriate root habitat selection model.

The five students judged the instructions as easy to follow, decided they could explain the experiment and results to a friend, and would recommend the lesson to a friend. When questioned on what aspect of the experiment they enjoyed, students listed learning how to care for plants and how to control variables as well as enjoying using their hands. Four students (80%) preferred completing the experiment on an individual basis. An aspect that could be improved was using group work for the harvesting and weighing process. Each student was able to reasonably answer a root habitat selection question concerning the role of peas in root competition; however, when challenged to design an original experiment testing root habitat selection models, students were unable to formulate a design.

Constructivist-Teaching Trial

In the constructivist-teaching approach, five groups composed of five students each, except for one with four students, developed an original experimental design over a 2-week period, including null and alternative hypotheses (Appendix M), and presented the plan to the teacher for review. Two submitted designs were original and not previously tested by the instructor, while the other three were designs original to the students but previously tested by the instructor (Appendix M). Groups not only discussed plans in lab class but several decided to meet after lecture class. The groups work collaboratively and cooperatively, except for group one for which the teacher frequently encouraged better communication. Nearly three-fourths of students preferred group work. While results of the evaluation survey indicated students direct questions to the teacher (Appendix O), instructor observations concluded that most questions were answered by other group members. Over 90% of the students asserted they could explain the experiment and results to a friend, and 86% would recommend the experience to a friend (Appendix O).

In terms of scientific results, groups three-five repeated instructor-tested experiments unknowingly and obtained outcomes in statistical agreement with previous trials. The above-ground measurements for group one, which proposed an original design not tested by the teacher, seemed to have no real trend. Statistical analysis indicated there was no effect of space or nutrients on the weight of roots or shoots; perhaps, the nutrients were in excess, even though the object was comparison of effects of low and high nutrient levels on fruit dry weight for plants in small and large spaces. The only difference lied in the dry weights of fruits between low and high nutrients for the larger

spaces. Group two compared nutrient levels and found the above ground flower and fruit

production differed in the latter weeks. The *p*-value for the dry weights was 0.08, only

slightly above the set alpha value of 0.05, but fruit biomass for the full strength nutrient

treatment was over twice the biomass of the half strength group.

For class discussions, groups two-five divided the discussion questions (Appendix

H) among members, but for group one, only a single member presented the oral report.

All group discussions addressed experimental design, results, interpretation of results,

and possible improvements with clear and logically deductive reasoning. Overall, the

written reports reflected the information presented in the group discussion. The only

exception lied in group one where only the member who adequately presented the oral

report understood the experiment and correctly interpreted the results.

When questioned about the aspect of the experiment enjoyed most, the top listings

were designing the experiment, working in groups, and manipulating plants. While over

30% of students did not have suggestions for improvements, 27% of the students

requested a longer growing period. Half of the students offered ideas and new designs

when challenged to create another root competition experiment, and 64% were able to

respond correctly to an application problem (Appendix O).

Model for Adapting Research Topics for the College Science Laboratory

Updating college curriculum in the teaching laboratory was dependent upon

adapting new research findings for instruction. The procedure used in the current study

was organized into a model, the GIST Model, for others to follow. The GIST Model had

4 broad components: (a) goals, (b) investigation, (c) selection, and (d) tests (Table 30). In

the first stage, the instructor was guided by course goals that included motivating

students, providing experience with advanced laboratory techniques, and opportunities to

practice critical and creative thinking, plus scholarship.

Table 30

GIST Model for Selection and Modification of Science Research for Teaching Laboratory

Step Name	Description
Guidance through Goals	Create a list of course goals, such as, bring research into the classroom; motivate students; provide students with opportunities to develop skills, critical thinking, and scholarly research; familiarize students with new scientific knowledge.
Investigation of Student Knowledge and Skills	Analyze general knowledge and lab skills by reviewing syllabi from pre-requisite courses, grade level, and graduation requirements.
Selection of Topic and Journal Articles	Review journal articles and literature reviews for topics at the appropriate level that complement lecture topics. Use Checklist to assess topic:

Criteria	Met?	
	Yes	No
Cohesive, Small Body of Knowledge		
Part of a Large Course Topic		
Meets Learning Objectives		
Improves Student Skills		
Adapts to Classroom Meeting Schedule		
Equipment and Facilities Available		
Supplies Affordable		
Potential for Student-Designed Experiments		
Incorporates Student Use of Technology		
Uses Statistical Analysis		
Potential for Reproducible Results		

Step Name	Description
Tests and Plans Initiated by the Instructor	Select species that meets specific requirements, such as readily available, easily manipulated, hardy after manipulation, and appropriate life cycle staging. Adjust the laboratory techniques to match classroom facilities, student skills, and classroom meeting schedule.
	Modify and test experiments reported in the literature to suit classroom use. In first trial, use a broader design to test timing, variables, and environmental controls. Revise experiment based on first trial, then perform at least one more trial. Compare results to published results and adopt if in agreement.
	Design original experiments and evaluate using same format as modified experiments.
	Plan instructional design using the ADDIE Model or another comparable model.

Previous student preparation and skill level had to be investigated so that goals were set for the appropriate instructional level. Examination of syllabi from prerequisite lecture and laboratory courses, grade level, and graduation requirements provided an understanding of theoretical knowledge and experience with the scientific method and statistical analysis. Knowing competencies and course goals guided selection of research topics reported in the scientific literature.

Selection of a research topic began with reading journal articles and literature reviews of subjects matching or supplementing the course goals. The selected topic represented a smaller body of knowledge that supported a larger concept already addressed in lecture. Additional research articles that further investigated the topic were located, read, and assessed. To better evaluate the topic as worthy of selection, attributes were rated using a checklist (Table 30) with all affirmative responses indicating a subject with high likelihood for success. The final decision about potential success resided in laboratory testing by the instructor, the most labor-intensive and crucial step within the model.

Instructor testing, the fourth step, modified the research methods for the available laboratory facilities and student participants, plus designed and tested a series of experiments. Modification of methods reported in the literature included species selection, refinement of handling and manipulation techniques, equipment substitution, and staging of life cycle and protocols to fit weekly classroom meetings. A checklist was used to assess successful modification of technique before experiments were designed (Tables 7 & 8). Initially, laboratory experiments were developed by modifying the actual research reported in the literature to fit within the confines of a teaching laboratory.

Qualitative and quantitative data were collected, subjected to statistical analysis, and compared to outcomes reported in the literature. Agreement with the research literature and further assessment of feasibility for classroom use preceded adoption of a new lab experience for students. Subsequently, the instructor designed original experiments that added new scientific knowledge and that prepared the instructor to better respond to possible experiments students may design. Again, design was followed by testing and assessment. When outcomes were repeated in two or three trials, these new designs were ready for classroom use. The initial trial tested timing, variables, and environmental controls. The second trial tested improvements and outcomes to determine whether the experiment was classroom ready. Repeated trials ensured reproducibility of experiments and addressed problems students may encounter. Once the instructor was satisfied with the research quality, instructional design was planned using a model, such as the ADDIE Model, as a guide (Table 30).

Only through further testing by others will the value of the GIST Model be determined. Whether it is useful for only the Biological Sciences, or Biology courses devoted to experiences with living organisms, or to courses in the chemical and physical sciences remains to be seen.

CHAPTER V

DISCUSSION

The discussion was broken down into 4 sections: (a) instructor experimental designs and tests, (b) instructional plans, (c) field trials, and (d) the GIST Model. Instructor modified experiments were compared to results in the literature, while original designs were dissected for possible improvements. The use of the ADDIE Model as an instructional plan in designing the teaching of college laboratory experiments were evaluated as well as the probable benefits and disadvantages of the objectivist- and constructivist- teaching strategies. Conclusions about the validity of instructional plans were based on observations of limited field trials. The last portion of the study was dedicated to the GIST Model for Selection and Modification of Science Research for the College Teaching Laboratory and its applications and future use.

Instructor Experimental Designs and Tests

A discussion of instructor results included conclusions about each trial, possible improvements to the design, and proposed designs for future testing. Also, these results were described with the teaching classroom application in mind, especially scheduling around normal class meetings.

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Fence-Sitters Versus Owners

The results of each of the three trials for the adapted fence-sitter versus owner experiments indicated Sugar Ann English peas exhibit the resource matching response; unlike Kenyan beans that competed using intra-plant avoidance response (Maina et al., 2002). The root, shoot, and flower/fruit masses, as well as above-ground observations, showed that there was little difference between fence-sitters and owners. In the first trial, the experimental feasibility was demonstrated, and 4 weeks was selected as the termination point for subsequent trials. However, a time span of 5 weeks or later could have been feasible, but weeks in laboratory classes were limited and the extension of 1 or more weeks means possible elimination of other valuable experiments.

In the second trial, water and nutrients were increased because of wilting and yellowing of leaves recorded in the first attempt. There was slightly more shoot production in the second trial, an expected result because extra nutrients favored increased shoot growth over root growth (Russell, 1977). In addition, increased growth indicated nutrients and water were possibly limiting in the first trial.

In the third trial, fence-sitters and owners were incubated under greenhouse conditions. Flower production was delayed by 1 week, and fruits were not apparent at the 4-week termination point. However, fence-sitters and owners responded similarly and were not statistically different in root, shoot, and flower masses, again confirming resource matching as the mode for root competition. While positioning the plants in a greenhouse yielded similar results about habitat selection models as the other trials using light bench conditions, the reduced control of environmental conditions seemed to delay

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flower and fruit production and was recommended as the plant incubation condition only if a laboratory light bench is unavailable.

Even though peas seemed to exhibit the resource matching response, when Kenyan beans were utilized in the fence-sitter versus owner experiment (Maina et al., 2002), the fence-sitters produced substantially more roots than the owners, an intra-plant avoidance response. Since plant species compete using different strategies, additional experiments might use other plant species. Experiments designed to test excess nutrients or the restriction of certain macro- or micro-nutrients were recommended, especially for directed research studies.

Hydroponic Fence-Sitters Versus Owners

While no literature exists to compare the results of the hydroponics design, outcomes can be discussed with the previous set of experiments in mind. Like in the vermiculite-grown plants, the hydroponic fence-sitters and owners did not differ in terms of root, shoot, and flower/fruit mass or in above-ground observations for the two trials, thus indicating the resource matching response described root competition. In the first trial, the low light intensity probably caused the smaller root and shoot mass, an observation reported by others (Ericsson, 1995). For the second trial, the light intensity was increased but was still less than the fence-sitters versus owners light bench conditions. While the plant mass was similar between treatments, the large fruit weight compared to the root and shoot weight was unexpected. The vermiculite and hydroponic designs, if repeated simultaneously, ought to be compared to determine whether there

were statistical differences. Flower/fruit mass obtained in the teaching classroom was closer to results of the first trial, thus indicating the need for further experimentation.

Several improvements were recommended for the hydroponic apparatus, including expansion to accommodate a larger sample size of fifteen to twenty units. Larger sample size improves the validity of statistical tests (Zar, 1999). In addition, increased light intensity to match the light bench conditions would determine whether differences in the timing and mass of flowers and fruits between hydroponic- and vermiculite- grown plants was attributed to light or root support methods. Also, the hydroponic apparatus could be utilized to repeat other experiments, such as the fence-sitter versus the single-root plant.

Fence-Sitters Versus Single-Root Plants

The experimental design was based on literature (Gersani & Sachs, 1992) that also employed peas as the species of interest. In the first instructor trial, the root and shoot mass of the fence-sitter and single-root plant was similar; however, the flower/fruit mass differed in the fourth and fifth weeks. In terms of above-ground measurements, the number of flowers and fruits also differed. Even though the results for reproductive structures were not similar, the two treatments produced equivalent root mass indicating the resource matching response as the possible habitat selection model. To determine if water and nutrients were limiting, they were increased in the second trial and 4 weeks was chosen as termination point to minimize use of classroom time.

Increased water and nutrients for the second trial improved flower and fruit yield; however, timing and quantities were nearly identical for the two treatments, indicating

resource matching response continued to explain root competition of peas. Water and/or

nutrients were limiting in the first trial based on improved yields. The excess resources

enabled the single-root plant to not only make up the difference in root mass, but also

matched the fruit mass of a plant that began with twice the root mass. The results of the

second trial agreed with those reported in the literature (Gersani & Sachs, 1992).

Further comparisons of fence-sitters and single-root plant were warranted. Similar

designs could question if the starting root mass determines the ending root mass when

excess nutrients are available. For example, an experimental design could use a single-

root plant versus a tri-root plant, a 1:3 ratio for initial root mass (Figure 63), and results

compared to the 1:2 ratio tested in this study and by other investigators (Gersani & Sachs,

1992).
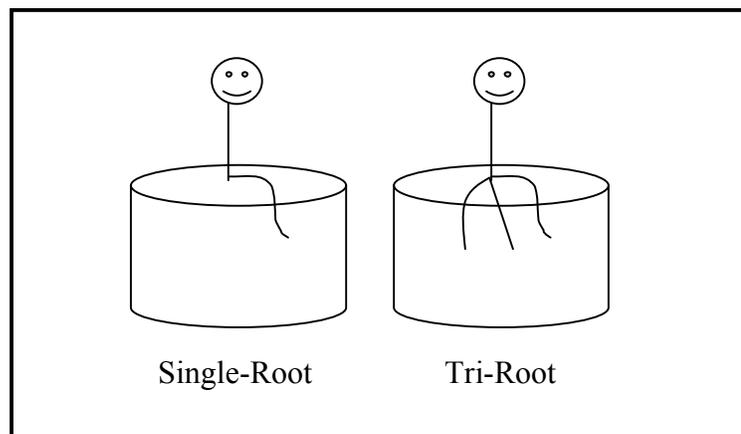
Figure 63. Single-root plant versus tri-root plant.

Split-Root Plant Versus Two Single-Root Plants

Because this design comparing equal root mass but unequal shoot mass was

original, there does not exist scientific literature for comparison. In both trials, the nearly

equivalent root mass was sustained, indicating that peas were employing a resource matching response. The similar root mass seemed to support nearly identical flower/fruit mass even though the pot with two single-root plants had twice the shoot mass initially. In the first trial, the shoot mass was similar between treatments by the fourth week, but statistically different in the fifth week. In the second trial terminated at week 4 and receiving increased water and nutrients, statistical differences in shoot mass were measured a week earlier than trial one (week 4 instead of week 5). Whether the added water and nutrients accelerated plant development or changed the effects of root competition or shoot mass was unclear. Further experimentation to elucidate effects of root competition on the root-shoot ratio and reproductive biomass that enhances the current design would be valuable.

Two Fence-Sitters Sharing a Space

The fifth experimental design was also original and did not have scientific literature for comparison. In both trials, the mass of the roots and the space in the small pots was equivalent to the root mass and space in the large pot. Because root mass did not differ in the presence or absence of competitors, but matched available resources, the peas seemed to illustrate the resource matching response. While the design was straightforward, a major flaw was that above-ground measurements could not be compared. A better design might have overcame this defect if the two treatments had shoots experiencing different conditions (Figure 64). In this design, the shoot mass of partitioned plants is comparable to that of non-partitioned plants. Flower/fruit mass is

treated like shoot mass, but root mass is evaluated at two levels, between pot sizes as in

the original design and between partitioned and non-partitioned treatments.
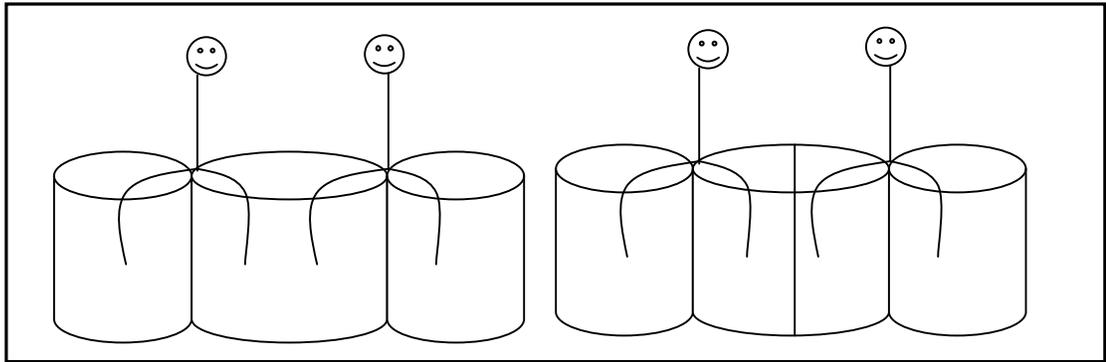
Figure 64. Possible improved design for two fence-sitters sharing a space.

Light Bench and Cold Conditions

An important discovery found prior to field trials was that peas grown under

continuous light did not flower. In peas, induction of reproduction occurs after the plants

experience a photoperiod transition from short to long days (Howell, 1998). However,

peas can bypass the photoperiod requirement if the seed is exposed to a cold treatment.

In the process of creating split-root plants using the protocol modified for the classroom,

peas were incubated in a cold environment for 2 weeks, a long enough time period to

promote flower and fruit development.

The simple light bench constructed with inexpensive shop lamps and lumber was

recommended for college classrooms that lack access to an environmental chamber. The

ambient room conditions maintained by central heat and air conditioning proved reliable

enough to avoid introducing fluctuating variables encountered in the greenhouse. The

light intensity of 2,152 lux emitted by fluorescent lamps suspended 61 cm above the pot

surface was sufficient for pea seedlings to mature and complete the reproductive cycle within 4 weeks, a relatively short response time feasible within the time constraints of the college teaching laboratory

Instructional Plans

A number of well-known instructional design plans, such as the Dick and Carey Model (2001) or a combination of several design models, were possible choices for this research project; however, the ADDIE Model was most appropriate for at least three reasons: (a) its simplicity, (b) its adaptability, and (c) its promotion of a repetitive, critical review necessary for good science (Figure 5). The straightforwardness and only five steps of the ADDIE Model made the instructional plan not only simple, but also easy to follow. While several models contain twice the number of steps as the ADDIE Model, the detailed process would have been initially overwhelming and difficult to remember. The acronym ADDIE (short for Analysis, Design, Develop, Implement, and Evaluation) enabled the user to recall the steps at any time, also adding to the simplicity of the model.

The ADDIE Model was highly adaptable to learning situations and theories of knowledge and was applied in a stepwise fashion in the current study. The initial analysis phase included the assessment of student skills and knowledge base as well as identification of objectives that occurred prior to topic selection. The design step involved selection of instructional and motivational strategies, and experimental design, and plans for assessing student learning and project success. At this point, various theories of knowledge were consulted for further design and development decisions, and the objectivist and constructivist strategies were applied. During development,

instructional handouts and aids were created for implementation in stage four, the limited field tests. Evaluation occurred during each of the previous four steps and revisions were made on a continuous basis. What actually occurred within each stage varied with each field trial, and new requirements were added or removed depending on the situation, a further testament to the value and adaptability of the ADDIE Model to science laboratory teaching.

In the ADDIE Model, employing critical evaluation at every stage was an introspective process that resembled the analytical methods of the scientist. A scientist often endeavors to investigate an idea or concept using the scientific method, employing evaluation at every turn to refine experiments so that he or she can accurately investigate the hypothesis and outcomes receive precise interpretation. Also, the other general stages of the scientific method are parallel to the first four steps of the ADDIE Model. For example, the scientist analyzes if a topic or idea warrants investigation, designs an appropriate experiment with null and alternative hypotheses, develops parameters, and implements the experiment. Evaluation of experimental outcomes and research design were the capstones; therefore, the normal activities of scientists and application of scientific method were synchronous with the ADDIE Model, making it ideal for science education.

Field Trials and Observations

As with most instructional design models, an initial, small field trial was desirable during the implementation phase. While lack of repetition and small sample size hinder validity, general observations provided insights. Based on fieldnotes, student evaluations,

and student reports, teacher impressions permited assessment of possible positive and negative outcomes as well as revisions for the next round of trials. However, larger sample size and repeated trials would be required to validate the success of each teaching strategy. If a comparison between two prominent teaching paradigms was the objective, then the field trials needed a substantially different design than the one presented in this study.

Objectivist-Teaching Trial

In the objectivist-teaching trial, the feasibility of placing the split-root technique in the hands of students, the reproducibility of student results, the fulfillment of learning objectives, and the enjoyment and motivation experienced by students were evaluated for positive outcomes. Instructor observations determined that students were not only able to create split-root plants, but also that no plants underwent senescence or death, illustrating the practicality of the classroom modified technique as well as the hardiness of the species selected. In addition, all student results agreed with the instructor-tested outcomes, demonstrating the reproducibility of the teaching experiment and avoiding student frustration that might be encountered if results were conflicting or confusing. As verified through the acceptable oral and written reports, students met the objectives of the lesson and appropriate skills were developed. The perceived student enjoyment during the project period and unanimous, positive responses on the student questionnaire were evidence of project success and indicated the goal of student motivation was met.

While several constructive outcomes were found during the application of objectivist-teaching paradigm, negative aspects also were identified leading to potential

revisions. One probable disadvantage was a lack of interaction among students and peer-induced learning since most discussions and questions were directed toward the instructor. Also, students suggested at the end of the experience that they would have benefited from working in groups, especially during the harvesting and weighing process. Thus, in an improved field trial, students would work together to complete time-consuming tasks because organizing and sharing tasks among students are crucial features in group learning experiences. Another potential solution is to give students more time for harvesting and weighing plants because the recommendation for group work may arise from a feeling of being overwhelmed if the time allotted for tasks is too short. Group work may provide more opportunity for critical thinking tasks.

Another negative aspect of the objectivist strategy was revealed when students were unable to create an original experimental design when challenged on the project evaluation form. The objectivist instructional plan should be modified to include more exercises in critical thinking, especially in the area of experimental design. For example, a concluding activity could require student groups to develop a new design testing root competition. Each group interacts and communicates to prepare and present the plan orally to the class with an ensuing discussion that identifies positive points and possible improvements for the student design.

Based on fieldnotes, several conclusions about experimental protocols were possible. For instance, students were successful with application of the split-root technique and should perform this task in its entirety in all future field trials because it advanced laboratory skills and lessened the preparation tasks for the instructor. To improve above-ground observations, stem height was added to the measurements, and a

better diagram of plant parts was needed. Teacher notes and observations were crucial for thinking about possible improvements. It is expected that larger field trials would reveal new problems, and as with most aspects of teaching, revisions would occur after every trial. Only more numerous and larger field trials would have provided sufficient data for statistical analysis of project success.

Constructivist-Teaching Trial

There were many positive outcomes in the field trial using constructivism as a teaching strategy. Students crafted split-root plants from seeds and maintained plants throughout the experiment, proving to the feasibility of the classroom methods and capability of students. Students assumed a more active role and groups met after class to talk about design proposals and other experimental issues. They presented their design and information collaboratively and accurately, indicative of groups working well together. Unknowingly, three groups proposed experimental designs already tested by the instructor, and group results agreed with those obtained by the instructor, demonstrating the reproducibility of outcomes. Learning objectives were met for most members of the class, that is, the students formulated and performed a new design and properly interpreted the results as well as developed appropriate laboratory skills. Most students responded on an exit questionnaire that they would recommend the experiment to a friend, and teacher fieldnotes on the positive interactions within groups and the enthusiasm with which tasks were undertaken confirm both pleasure and motivation as project achievements. On the student evaluation form students were able to design

another root competition experiment, attesting to the development of critical thinking skills, a major learning objective.

Although there were numerous encouraging outcomes, several problems that require solutions were discovered in the small trial. For example, in group one, a single group member controlled the group interactions and presentation. In the future, the domineering group member should be counseled privately by the instructor to develop better communication skills and assist others with learning how to participate. Another potential solution is to limit group-work to the design phase and assign specific roles to each member.

The lack of communication in group one might have explained the conflicting data reported. While the class presentation for group one included accurate information and result analysis, the individual lab reports of the members, except for the dominant person, were inaccurate and displayed a lack of understanding. Consequently, if group work is employed, individual reports are necessary to measure whether learning occurs on an individual basis. Individual written assignments employed to evaluate group work must continue in subsequent trials.

Another potential drawback in the constructivist teaching strategy was the potential for students to propose designs not already tested by the instructor. Two untested designs were developed by students in the constructivist field trial. The instructor was probably not able to guide the students as effectively as the groups proposing teacher-tested designs. If time and space allowed, the instructor or a student assistant teacher could have tested the new designs to potentially offer better advice during student trials, especially for complex designs, such as the one proposed by group

one. Otherwise, the instructor must have used deductive reasoning to anticipate problems and outcomes, plus reviewed research progress more frequently. One benefit of using split-root plants was the numerous designs possible. With limited time for design testing, the instructor likely would encounter new designs that required critical scrutiny, and perhaps, modifications before issuing approval for initiation. Although the adage says learn from mistakes, the novice sometimes becomes irreversibly frustrated before the learning occurs.

In developing plans for project revisions, student input and perceptions were taken into consideration. Even though current students suggested that the experiment lasts longer, the possible experimental portion to lengthen was increased number of weeks of plant growth. However by the fourth week of plant growth, students have mastered plant handling and taking above-ground measurements, so adding weeks does not improve skills, but actually reduces time available for other topics.

The GIST Model

The proposed GIST Model (Table 30) was a guide for college instructors to bring new scientific experiments into the classroom. The instructor first listed the goals for the new experiments, such as motivating students and providing students with opportunities to develop skills, critical thinking, and scholarly research. Investigation of student knowledge and prior skills was followed by selection of a topic and materials. The teacher then planned and tested potential experiments for classroom use through a time-consuming but crucial process.

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The benefits of the GIST Model (Goals, Investigation, Selection, Tests) were found within each step. The first step stressed the need for designing college teaching experiments with well-defined goals such as increasing student interest, lab skills, knowledge, and critical thinking. The investigational phase ensured that experiments were developed at an appropriate level for students, that is, not too elementary, yet not overwhelming. A checklist for guiding the selection of topics enabled the college instructor to determine in a quick manner whether the topic was suitable thus, saving time possibly wasted on a topic that did not met criteria. For the final stage, the instructor was presented a general plan for testing experiments and modifying protocols using a proscribed pattern of repetition and revision. Classroom tests of experimental and instructional designs concluded the process. Overall, this plan not only helped to guide the instructor, but also might encourage teachers to continue to bring new scientific knowledge into the teaching laboratory.

The employment of the GIST Model had and has implications for students, teachers, and administrators. For example, students benefited from learning and replicating new research found in the literature. Their critical thinking skills were sharpened with novel opportunities to design, develop, and execute original experimental designs. Using the GIST Model as a guide, teachers could be encouraged to keep their students, as well as themselves, current with recent scientific advances. Administrators might direct teachers to utilize the GIST Model to create new laboratory experiences for the classroom.

While there are potential advantages to the GIST Model, there were also limitations. The model needs further testing to determine usefulness and validity. These

questions cannot be answered in this present study. However, another study might focus on these crucial issues by having college instructors employ the GIST Model to design and teach new research experiences. As with any model, revisions and improvements are always possible and desirable to continually increase the strength of the model. Also, investigation into whether the model can be employed in non-living biology courses or in other science courses, like chemistry and physics, as well as on another teaching level such as secondary education, requires testing and evaluation. If found to be relevant, then the GIST Model would have extensive application.

This study added not only to scientific knowledge, but also to the instructional design and science education research as well. The adapted and original root competition experiments agreed with and augmented current scientific knowledge on habitat selection of peas. The GIST Model, after further testing and possible revision, presented an instructional design plan for selection and modification of science research for the college teaching laboratory.

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APPENDIXES

Appendix A

Institutional Review Board Approval Letter

Research and Sponsored Programs
Building 11, Room 109
11000 University Parkway
Pensacola, FL 32514-5750

May 18, 2006

Ms. Shannon Elliot
3650 Bayou Blvd.
Pensacola,, FL 32503

Dear Ms. Elliot:

The Institutional Review Board (IRB) for Human Research Participant Protection has completed its review of your proposal titled "Teaching Original College Science Lab Experiments: Habitat Selection Model of Sugar Ann English Peas" as it relates to the protection of human participants used in research, and has granted approval for you to proceed with your study. As a research investigator, please be aware of the following:

- You acknowledge and accept your responsibility for protecting the rights and welfare of human research participants and for complying with all parts of 45 CFR Part 46, the UWF IRB Policy and Procedures, and the decisions of the IRB. You may view these documents on the Office of Research web page at http://www.research.uwf.edu. You acknowledge completion of the IRB ethical training requirements for researchers as attested in the IRB application.

- You will ensure that legally effective informed consent is obtained and documented. If written consent is required, the consent form must be signed by the participant or the participant's legally authorized representative. A copy is to be given to the person signing the form and a copy kept for your file.

- You will promptly report any proposed changes in previously approved human participant research activities to the Office of Research and Sponsored Programs. The proposed changes will not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the participants.

- **You are responsible for reporting progress of approved research to the Office of Research and Sponsored Programs at the end of the project period. Approval for this project is valid for one year. If the data phase of your project continues beyond one year, you must request a renewal by the IRB before approval of the first year lapses. Project Directors of research requiring full committee review should notify the IRB when data collection is completed.**

- You will immediately report to the IRB any injuries or other unanticipated problems involving risks to human participants.

Good luck in your research endeavors. If you have any questions or need assistance, please contact the Office of Research and Sponsored Programs at 857-6378.

Sincerely,,

Dr. Keith Whinnery, Chair
IRB for Human Research
Participant Protection

Ms. Sandra VanderHeyden, Director
Research and Sponsored Programs

cc: Dr. Peggy Winter

Appendix B

Student Consent Form

Student Consent Form

The purpose of this study is student testing of several original 8-week science experiments concerning habitat selection models of peas. Outcomes will be incorporated anonymously into an Ed.D. dissertation. Data will include observations, filednotes, student data sets, student reports, and project evaluations coded to conceal the identity of the student. Grades for student reports will be confidentially reported to the professor of record for approval. The student's name will not be associated with any findings of this study and the student participates voluntarily with the right to ask questions before, during, and after their experience.

There are no known risks to attending and participating in these original science experiments. On the contrary, the student will benefit from this experience through learning about experimental design and scientific ideas presented in current science literature and demonstrated through the experimental process.

The signature below grants permission to Shannon S. Elliott to use data described above anonymously in her Ed.D. dissertation or any publication emanating from the dissertation. Students will receive a copy of their signed consent form.

_____   _____

Student Signature   Date

_____   _____

Shannon S. Elliott   Date

Shannon S. Elliott, Ed.D./Science Specialization Student
selliott1@uwf.edu

IRB Requirement

Appendix C

Objectivist- Teaching Handout Sample

Procedure for Week 3

Method:

Each student is responsible for fashioning two equal roots for 16 pea plants. These split-root plants will then be utilized in the fence-sitter versus owner set-up.

1. Obtain a beaker full of rag-dolls.
2. Carefully unroll the rag-doll and remove the top paper towel.
3. Lateral roots should have formed off the entire length of the radicle. At the cut tip, there should be three lateral roots that are roughly the same length (Figure 1). However, if there are not three roots at the distal end, see if there are two roots that are roughly the same size (Figure 2).
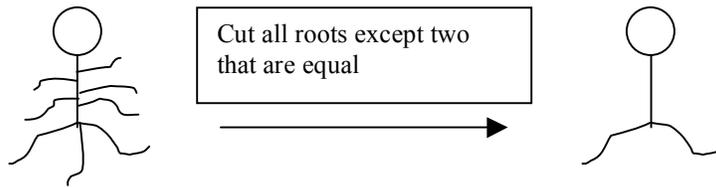
Figure 1: Three equal roots at cut surface of radical
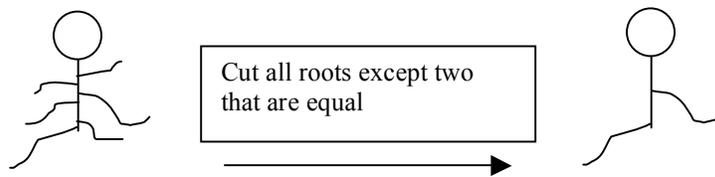
Figure 2: Two equal roots on the radicle

4. Using a razor blade or your clean fingers (easier), remove all lateral roots EXCEPT two lateral roots that are approximately the same length (Figure 3). DO NOT CUT THE ROOTS TO MAKE EQUAL LENGHTS.
5. Try to fashion each split-root plant so its roots are roughly the same amount as the other split-root peas. Place any plants that have all unequal lateral roots in the container with water (label container: unequal roots).

Figure 3: split-root pea plant

6. Place the split-root plant in a weigh boat or other container filled with water (label container: split-root plants).
7. Repeat until there are 16 split-root plants.

Fence-sitters v Owners in Vermiculite
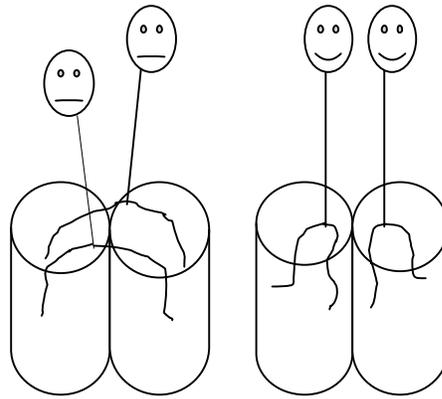
Figure 4: Fence-sitters v Owners

1. The objective is to create 4 fence-sitter scenarios and 4 owner scenarios (Figure 4)
2. Obtain 8 small planting trays that have openings across from each other. In a well-ventilated area, preferably outside, and using a mask, fill 2 openings across from each other ¾th full with vermiculite (inert potting mix) for each tray. Wet the vermiculite.
3. For each tray, place 2 skewers on the inside opposite corners in the vermiculite.
4. For each fence-sitter scenario, stake a split-root pea to each skewer using thin Velcro strips. Then place one lateral root in each opening (Figure 5). Immediately after staking the plant, gently add vermiculite to both openings on both trays. YOU MUST WEAR A MASK for vermiculite contains small, airborne particles.
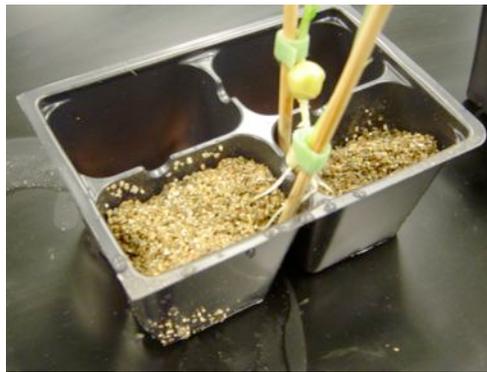
Figure 5: Fence-sitter set-up.

5. Rewet the vermiculite: add 60 ml of water to both openings. IT IS IMPERATIVE that the roots do not dry out.
6. Label fence-sitter scenarios: fence-sitter 1 a/b, fence-sitter 2 a/b, fence-sitter 3 a/b, and fence-sitter 4 a/b.
7. For each owner scenario, stake a split-root pea to each skewer using thin Velcro strips. Place both lateral roots of each plant into only one opening (Figure 6). Immediately after staking the plant, gently add vermiculite to both openings on

both trays. YOU MUST WEAR A MASK for vermiculite contains small, airborne particles.

Figure 6: Owner set-up

8. Rewet the vermiculite: add 60 ml of water to both openings. IT IS IMPERATIVE that the roots do not dry out.
9. Label owner scenarios: owner 1 a/b, owner 2 a/b, owner 3 a/b, and owner 4 a/b.
10. Carefully transport the LABELED fence-sitters and owner scenarios (name, date, class time) under continuous growth light. A container or plate at the base of the trays will be needed to collect excess water. Place the plants so that the order is random, meaning that all the fence-sitters are next to each other (Figure 7).

O	FS
O	FS
O	FS
O	FS

a

FS	O
FS	FS
O	O
O	FS

b

Figure 7. Owner (O) and Fence-sitters (FS) are not randomly placed (a), where in (b) they are randomly placed (FIGURE 7 WAS ADDED AS A REVISION)

11. Three times a week, the pea seedlings will be saturated with half strength Hoagland's media. Occasionally the pea seedling will be watered with distilled water to prevent accumulation of ions in the vermiculite.

Appendix D

Constructivist- Teaching Handout Sample

Group Design

As a group, discuss and decide upon a scenario design.	
Draw a picture of your scenario comparison.	Example: Fence-sitter v Owner Fence-sitters Owners
How many split-root and/or single-root plants will you need for 6 scenarios of each?	For 6 fence-sitter and 6 owner scenarios, 24 split-root plants are required.
Write the null (H_o) and alternative (H_a) hypothesis.	Example: H_o: mean of the roots for fence-sitters = mean of the roots for owners mean of the shoots for fence-sitters = mean of the shoots for owners mean of the fruits for fence-sitters = mean of the fruits for the owners In equivalent language, the fence-sitters and owners are not different in regards to the roots, shoots, and fruits (resource-matching) H_a: mean of the roots for fence-sitters ≠ mean of the roots for owners mean of the shoots for fence-sitters ≠ mean of the shoots for owners mean of the fruits for fence-sitters ≠ mean of the fruits for the owners Fence-sitters and owners are different in at least one of the following: root, shoot, fruits (not resource matching)
Based on your design, what statistical test will you employ (ask the teacher)	Example: Use Hotelling's T^2 test
HAVE THE TEACHER APPROVE OF YOUR DESIGN _____(teacher's initials)	

Fashioning split-root plants (and single-root plants, if needed)
Each group is responsible for fashioning the appropriate number of split-root plants and single-root plants as needed for their design.
  1. Split-root creation: Using a razor blade or your clean fingers, remove all lateral roots EXCEPT two lateral roots that are approximately the same length (Figure 1 or 2). DO NOT CUT THE ROOTS TO MAKE EQUAL LENGHTS!!!
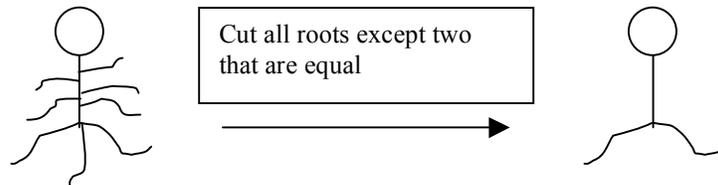
Figure 1. Three equal roots at cut surface of radicle
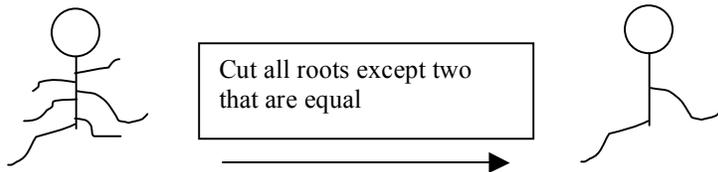
Figure 2. Two equal roots on the radicle

  2. Single-root creation (Figure 3)
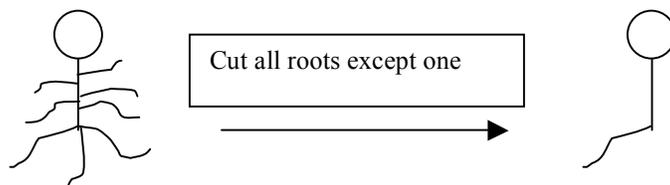
Figure 3: Single-root plant from plant in ragdoll

Creation of your scenarios
  1. Fashion the split-root and/or single-root plants in your designed scenarios.
  2. Place skewers where the plants will be located and use skewers to keep them in place.
  3. If using vermiculite, YOU MUST WEAR A MASK for vermiculite contains small, airborne particles. In addition, wet vermiculite and do not let the roots dry out.
  4. Label scenarios clearly and randomly place them under your growth light set-up, meaning that all of the same scenarios are next to each other.
  5. The pea seedlings will be watered according to your design.

Appendix E

Lab Report Outline and Criteria Handout

RULES

- Include headers (Abstract, Introduction, Material & Methods, Results, Discussion, and Reference) followed by paragraph(s) that address the bulleted list under the header in the following guidelines.
- Cite at least one journal article or book pertaining to plant habitat selection.
- Write in THIRD PERSON not first person (example: Write "Data were collected" instead of "We collected data").
- Double Space throughout the paper
- Times New Roman, 12 point font
- There is no minimum or maximum paper length, just thoroughly complete this assignment using the following guidelines.
- The paper is due Dec 1. Note that the due date is a Friday, and not a normal lab period.
- Lab reports may be submitted in either hard copy or electronic formats.
  - If you elect to submit your report as a hard copy, you may either give your report to Dr. Fox, Shannon Elliott, or Allyson Bradley or place your report in the box outside 58/108.
  - If you elect to submit your report electronically, please name the file that you submit as "PlantBiotech-LabReport1-yourname" where "yourname" is your last name. Email your report as an attachment to tfox@uwf.edu; please place "Plant Biotech Lab Report" in the subject line of your email. You will receive a reply email within 24 hours indicating that I have received your report; if you fail to receive a reply, please contact me immediately.

GRADING BREAK DOWN

- Attending and participating in all sessions, entering data in Excel .... 50 points
- Abstract .... 5 points
- Introduction .... 10 points
- Material & Methods .... 10 points
- Results .... 10 points
- Discussion .... 10 points
- References .... 5 points
- **Total .... 100 points**

HABITAT SELECTION MODEL OF PEAS
REPORT GUIDELINES

ABSTRACT

Purpose: Briefly describe what the experiment was about and the results

1. State the hypothesis in your own words in terms of 3 habitat selection models.
2. Brief overview of design: fence-sitter v owner
3. Conclusions: Which habitat selection model did the Sugar Ann English pea follow?
4. This section should be 1 paragraph.

INTRODUCTION

Purpose: Provide introductory information to set the stage for the rest of the report

1. Briefly explain the three habitat selection models:
   1.1. Inter-plant avoidance
   1.2. Resource matching
   1.3. Intra-plant avoidance
2. Explain the split-root technique
   2.1 What is it?
   2.2. How can it be used to determine the habitat selection model of plants: briefly discuss design
3. Present the hypothesis that is being tested that is supported by the design.
4. In this section, use at least one reference.

MATERIALS & METHODS

Purpose: Describe the protocol and procedures that were employed

1. Briefly describe the experimental design
   1.1 The initial set-up was
       1.1.1. Ragdoll, cut distal ends, split-root/single-root
       1.1.2. Placing them into scenarios
   1.2. Observational data was taken for the following weeks
       1.2.1. Leaves, tendrils, height
       1.2.2. Flowers and fruits
       1.2.3. Other observations
   1.3. Then we took dry weight determination of Roots, Shoots, and Fruits
       1.3.1. Using crucibles
       1.3.2. Dried out for a week to remove water
2. Describe how data was analyzed
   2.1. Calculated means for comparing leaves, tendrils, height, flowers, and fruits
   2.2. Testing to see if the scenarios are the same in regards to above ground portions of the plants.

2.3. t-squared test for comparing roots, shoots, and fruits (Dr. Pomory's program)

2.4. Testing to see if scenarios are the same in regards to roots, shoots, and fruits

3. Briefly describe the molecular technqiues employed.
   3.1. Tissue harvesting and storage

   3.2. Protein analysis
      3.2.1. Protein extraction
      3.2.2. Protein quantitation
      3.2.3. NEpHGE-SDS-PAGE
      3.2.4. SDS-PAGE

   3.3. RNA anlysis
      3.3.1. RNA extraction
      3.3.2. RNA quantitation
      3.3.3. RNA gel electrophoresis

RESULTS

Purpose: Present the results BUT DO NOT discuss what the results mean

1. Observational data
   1.1. Report the MEANS for the observational data for each week
      1.1.1. Leaf means for fence-sitters and owners
      1.1.2. Tendril means for fence-sitters and owners
      1.1.3. Height means for fence-sitters and owner
      1.1.4. Flower means for fence-sitters and owners
      1.1.5. Fruit means for fence-sitters and owners

   1.2. Report any additional observations that are significant

   1.3. Include Table 1 (make sure table is all on the same page)

Table 1. Observational Data for Weeks 4-7

	Week 4	Week 5	Week 6	Week 7
Scenario 1 Leaf Mean				
Scenario 2 Leaf Mean				
Scenario 1 Tendril Mean				
Scenario 2 Tendril Mean				
Scenario 1 Height Mean				
Scenario 2 Height Mean				
Scenario 1 Flower Mean				
Scenario 2 Flower Mean				
Scenario 1 Fruit Mean				
Scenario 2 Fruit Mean				

2. Report the means of the dry weights in words.
   2.1. Root means for scenarios
   2.2. Shoot means for scenarios
   2.3. Fruit means for scenarios

3. Include Table 2 (make sure all of the table is on the same page)

Table 2. Dry Weight Determination

	Scenario 1			Scenario 2		
	Root	Shoot	Fruit	Root	Shoot	Fruit
Mean						

4. Using the t-squared test what was the p-value?

5. Report the protein and RNA content of pea roots in Table 3.

Table 3. Protein and RNA Content of Pea Roots

	Protein (mg/gfw)	RNA (mg/gfw)
Control		
Scenario 1		
Scenario 2		

6. Present an NEpHGE-SDS-PAGE gel of pea root proteins.

7. Present an SDS-PAGE gel showing root proteins of Control, Scenario 1, and Scenario 2 pea plants.

8. Present an RNA gel showing ribosomal RNAs of Control, Scenario1, and Scenario 2 pea plants.

9. Present a graph of the polyribosome profile in pea roots.

DISCUSSION

Purpose: Discuss what the results mean

1. What does the observational data means mean?
   1.1. Compare the means across the scenarios.

   1.2. What does this difference or lack of difference mean? Which habitat selection model(s) does this follow?

2. Based on the p-value

   2.1. Fail to reject the null hypothesis or reject the null hypothesis

   2.2. What does this mean in terms of habitat selection?

   2.3. Peas follow which habitat selection model
      2.3.1. Intra-plant avoidance response
      2.3.2. Resource matching response
      2.3.3. Inter-plant avoidance response

3. Possible errors or flaws in the design

4. Possible ways to improve the design

REFERENCES

Purpose: Provide sufficient information for the reader to locate a reference cited in the text

1. Since at least one journal article or book was employed, a reference section is required.

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2. Cite in APA format (a helpful tool can be found at http://www.stylewizard.com/index.html)

3. Do not forget to cite the information in the text of the Introduction section.

   3.1. When paraphrasing information from the article below, make sure to cite it at the end of the sentence with this in parentheses (Gersani, Brown, O'Brien, Maina, & Abramsky, 2001).

   Gersani, M., Brown, J., O'Brien. E., Maina, G., & Abramsky, Z. (2001). Tragedy of the commons as a result of root competition. *Journal of Ecology, 89*, 661-669.

   3.2. When paraphrasing information from the article below, make sure to cite it at the end of the sentence with this in parentheses (Maina, Brown, & Gersani, 2002).

   Maina, G., Brown, J., & Gersani, M. (2002). Intra-plant versus inter-plant root competition in beans: avoidance, resource matching, or tragedy of the commons. *Plant Ecology, 160*, 235-247.

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Appendix F

Lab Report Grading Rubric

Habitat Selection Model Lab Report
Grading Rubric

Student Name _____

Requirement	Possible Points	Points Earned	Comments
Rules & Attendance • Headers clear & in correct order • Written in third person • Double Space throughout the paper • Times New Roman, 12 point font • Submitted on time • Attended all sessions & participated in group discussion • Entered data into Excel	50		
Abstract • Stated the hypothesis • Brief overview of design • Conclusions: Which habitat selection model did the Sugar Ann English pea follow? • Length= 1paragraph	5		
Introduction • Briefly explained the three habitat selection models • Split-root technique • Hypothesis • At least one source cited	10		

Material & Methods (Habitat Selection)
• Briefly described the experimental design
   o The initial set-up
   o Observational data
   o Dry weight determination
• Described how data were analyzed
	5		

Material & Methods (Molecular Techniques)
• Briefly described the molecular techniques employed.
   o Tissue harvesting & storage
   o Protein analysis
   o RNA analysis
	5		

Results (Habitat Selection)
• Observational data
   o Means
   o Observations
   o Table 1
• Dry Weight
   o Means
   o Table 2
• p value
	5		

Results (Molecular Techniques) • Protein and RNA content o Table 3 • NEpHGE-SDS-PAGE gel • SDS-PAGE gel • RNA gel • Graph of the polyribosome profile in pea roots.	5		

Discussion
• Observational Data
    o Compare the means across the scenarios
    o What does this difference or lack of difference mean?
    o Which habitat selection model(s) does this follow?
• Dry Weight
    o Fail to reject the null hypothesis or reject the null hypothesis
    o What does this mean in terms of habitat selection?
    o Peas follow which habitat selection model?
• Possible errors of the experiment
• Possible ways to improve the design
	10		

References • At least one reference • Correct APA format	5		
TOTAL	**100**		

Appendix G

Objectivist-Teaching Discussion Questions Handout

Habitat Selection Individual Presentation Outline (Objectivist-Teaching)

Set-up:
- What is the null hypothesis? Alternative hypothesis? Statistical test?
- What did you think would happen?
-

Measuring Observational Data:
- How do the means compare between fence-sitters and owners each week? Any trends?
- When did the # of leaves, tendrils and stem height taper off?
- When did you first see flowers? Fruits?
- Why did you we place our plants under continuous light? Cold period requirement?

Statistical Analysis:
- How do the means of the dry weights between groups compare?
- What p-value was obtained employing the appropriate statistical test?
- Reject or fail to reject the null hypothesis? If the answer is rejected, what did the follow up statistical tests point to as the difference?

Interpretation:
- Any evidence supporting or guesses for which habitat selection model the pea employs: Inter-plant Avoidance, Resource Matching, or Intra-Plant avoidance Response?

Errors/Improvements (IMPORTANT):
- Were the results what you expected?
- Possible reasons for errors?
- How could your design be improved?
-

Additional Questions For After Presentations:
- Compare and contrast the results for each individual?
- Group consensus for pea habitat selection model?

Appendix H

Constructivist- Teaching Discussion Questions Handout

Habitat Selection Group Presentation Outline (Constructivist- Teaching)

Set-up:
- Draw a Picture of your Design on the Chalkboard
- Clearly Illustrate where the roots were placed
- What are you comparing in this set-up?
- What is the your null hypothesis? Alternative hypothesis? Statistical test?
- What did you think would happen?
-

Measuring Observational Data:
- How do the means compare between groups for October 2 (1 week in scenarios)? October 9 (2 weeks in scenarios)? October 16 (3 weeks in scenarios)? October 23 (4 weeks in scenarios? Similar? Different?
- Any trends from week to week?
- When did the # of leaves, tendrils and stem height taper off?
- When did you first see flowers? Fruits?
- Why did you we place our plants under continuous light? Cold period requirement?

Statistical Analysis:
- How do the means of the dry weights between groups compare?
- What p value was obtained employing the appropriate statistical test?
- Reject or fail to reject the null hypothesis? If the answer is rejected, what did the follow up statistical tests point to as the difference?

Interpretation:
- Any evidence supporting or guesses for which habitat selection model the pea employs: Inter-plant Avoidance, Resource Matching, or Intra-Plant avoidance Response?

Errors/Improvements (IMPORTANT):
- Were the results what you expected?
- Possible reasons for errors?
- How could your design be improved? –Or- Present a follow up design.

Additional Questions For After Presentations:
- Compare and contrast the results of the group experiments to determine if one experiment supports another?
- Is there one habitat selection model that explains competition in Sugar Ann English peas?

Appendix I

Objectivist- Teaching Student Evaluation Form

Evaluation for Habitat Selection Model (Objectivist)

Directions: Neither Shannon Elliott nor Dr. Fox will view the results of your evaluation until grades for this project are recorded. Please check the box (agree, neutral, or disagree) that best applies to the following questions regarding this opportunity.

Questions Regarding the Extra Credit Opportunity	Agree	Neutral	Disagree
Were the instructions easy to follow?			
Are the handouts on elearning.uwf.edu helpful?			
Do you know more about plant habitat selection now than before this opportunity?			
Did you employ critical thought in this experiment?			
Were some parts of your learning self-guided?			
Would you have preferred to work as a group instead of individually?			
Did you view the teacher as more of an authoritative figure? -OR- Did you view the teacher more as a coach or facilitator?			
When you had a question was your first response to ask the teacher? -OR- When you had a question was your first response to ask a classmate?			
Could you explain this experiment and your results to a friend?			
Would you recommend this extra credit opportunity to a friend?			

What aspect of this experiment did you like?

What aspect of this experiment could be improved?

Would you be able to design an experiment that tests habitat selection using the split-root technique, like our fence-sitters versus owners experience?

> If you can think of one, please write or draw it below:

What would you expect for Sugar Ann English peas, if one root of a split-root pea experiences twice as much nutrients as the other root? Does competition play a role?

Appendix J

Constructivist- Teaching Student Evaluation Form

Evaluation for Habitat Selection Experiment (Constructivist)

Directions: Shannon Elliott nor Dr. Fox will view the results of your evaluation until grades for this project are recorded. Please check the box (agree, neutral, or disagree) that best applies to the following questions regarding this opportunity.

Questions Regarding the Extra Credit Opportunity	Agree	Neutral	Disagree
Were the instructions easy to follow?			
Are the handouts on elearning.uwf.edu helpful?			
Do you know more about plant habitat selection now than before this opportunity?			
Did you employ critical thought in this experiment?			
Were some parts of your learning self-guided?			
Would you have preferred to work individually instead of a group?			
Did you view the teacher (Shannon) as more of an authoritative figure? -OR- Did you view the teacher (Shannon) more as a coach or facilitator?			
When you had a question was your first response to ask the teacher? -OR- When you had a question was your first response to ask a classmate?			
Could you explain this experiment and your results to a friend?			
Would you recommend this experience to a friend?			

What aspect of this experiment did you like?

What aspect of this experiment could be improved?

Would you be able to design another experiment that tests habitat selection using the split-root technique?
        If you can think of one, please write or draw it below:

Based on what you know about the habitat selection model of Sugar Ann English peas, what light, spacing, and nutrient considerations would you make if planting them in a garden? Does competition from another plant play a role?

Appendix K

Objectivist- Teaching Fieldnotes Sample

Objectivist- Teaching
First session (Fence-sitter and Owner Set-Up)

Monday, March 13, 2006 First meeting of the Monday extra credit night class (making scenarios: fence-sitters and owners)	Location: Building 58A, Room 201 Time: 5:50 – 7:35 p.m. Students: Student 1, Student 2, and Student 3

Student 1 entered the classroom and took a seat around 5:50. Student 2 came in at 5:55 and Student 3 at 6:00. Student 1 and Student 2 talked about their test, which was the next day. (they were both anxious and worried, they discussed studying techniques).

In front of them were beakers with ragdolls of Sugar Ann English peas with cut distal roots, pots with wetted vermiculite and stakes, containers with water, Velcro strips, labels, handout for the classes instructions. In the middle of the table, there was a container with vermiculite.

Through using a PowerPoint that was projected on a screen, I first went over how to earn extra credit points: 1.5 points if attend all sessions and compute and record data to an Excel worksheet and another 1.5 points if a satisfactory report is written.

Next, I went over introductory information: root background information such as nutrition, what is habitat selection, what are the three models, what is the split-root technique? how we can use the split-root technique to determine the habitat selection model of Sugar Ann English peas? I also gave brief instructions on the procedure for today as well as what we are going to do for the remainder of the term.

The design calls for the use of vermiculite. Student 1 asked "what is vermiculite?" I gave a definition and talked about why we used it. I also pointed to it on the table (inert soil substitute that we can use to ensure that the only nutrients the plant receives is what we give it through watering with Hoagland's media). Masks are required when working with vermiculite

I walked them to the next room to show where the plants would be placed under continuous light.

I demonstrated how to make a split-root plant. I opened up a ragdoll and took out one of the plants and pinched off all but two equal roots. I gave students the option to cut the roots with a razor blade or with clean fingernails. I also told them not to use any plants that had a cotyledon with fungal growth or any other contamination. (Later Student 2 used a razor blade while the other students used their fingers).

I asked students to make as many split-root plants as they could and separate them into containers with water by the length of the split-root: smaller and larger. I explained that they need 16 split-root plants that are roughly the small length size. They could trade with their neighbors until they had the 16 plants. The plants were then set up in fence-sitter or owner scenario. I also demonstrated how to do this.

After 20 minutes, my introductory discussion was over and I announced that it was time to begin.All three students took ragdolls one at a time out of the beakers with water and tried to make split-root plants.

Student 2 asked "is this containment?" as he pointed to a cotyledon with a bright yellowing covering. I said "yes, good observation, we do not want to use it then right?" Student 2 said "right" Student 1 then asked if a plant she had was contaminated. I said that it was. (the students are confused about contamination, I should discuss it further). To the whole class, I pointed out an example of what the cotyledons should look like and to discard it if does not look like this because it was a growth or film over it. Student 3 said "okay" (she must have also been confused)

Student 1 asked if once she had a split-root plant could she cut the remaining roots so that they are the exact same size. I addressed everyone and said that no that it would be the same as removing the root and would not work. (I need to stress that the two approximately equal roots should not be cut, next time).

The students worked diligently to fashion split-root plants. When Student 2 had 12 split-root plants that were roughly the same he asked the others if they had 4 plants about the size of his. Student 1 said yes and gave him some of hers. Student 2 had several split-root plants that were longer. He gave those to Student 1. Student 2 made a couple more split-root plants that he gave to Student 3. Student 1 and Student 3 traded back and forth until they each had 16 split-root plants that were roughly the same length (I was impressed how well they helped out each other and shared their supplies). The students also used the Velcro strips effectively when staking their plants into position (These strips are a lifesaver, using string probably would not have worked nearly as well)

At roughly the same time, the three students each had 16 split-root plants. They each made 4 fence-sitter and 4 owner scenarios. Student 2 asked me to look over the way he was making both. He was doing it correct. Then Student 1 wanted me to check fashioning and Student 3 followed with the same request. (Since this was new material, they may have been questioning themselves, in addition, they knew that if the scenarios are not set up correctly now they will not have plants or correct data, at this point I am probably seen as an authority instead of a facilitator).

Once, they had fashioned their scenarios, I asked them to transport their plants on a cart to the other room and set up their plants randomly. The three students did this at roughly the same time. I watched as they placed the pots (they did not know what random placement was, I need to correct this) I used Student 2's plants as an example and the other rearranged their plants (I must be clear to Tuesday's group about placing plants randomly).

The three students cleaned up their space and left together. The class ended at 7:35 p.m.

Notes to self:
- Students worked together well: sharing split-root plants they made. However, most questions were directed towards me.
- Students wanted me to double check when they made the fence-sitter and owner setups.
- At this point, students questions were mainly on the procedure.

Ways to improve:
- Overall, the class seemed to run smoothly, but definitely room for improvement
- Stress that you do not cut the roots of a split-root plant to make even
- Next time make sure to better explain about contamination and random placement.

Tuesday, March 1, 2006 First meeting of the Tuesday extra credit morning class (making scenarios: fence-sitters and owners)	Location: Building 58A, Room 201 Time: 9:17- 10:35 a.m. Students: Student 4 and Student 5

Student 4 and Student 5 entered together laughing and talking at 9:17 (they must be friends). They chose seats next to each other and looked through their handouts.

In front of them were beakers with ragdolls of Sugar Ann English peas with cut distal roots, pots with wetted vermiculite and stakes, containers with water, Velcro strips, labels, handout for the classes instructions. In the middle of the table, there was a container with vermiculite.

I asked them if they wanted to start early since technically the class was to begin at 9:30. They both said "yes."

Through using a PowerPoint that was projected on a screen, I first went over how to earn extra credit points: 1.5 points if attend all sessions, and compute and record data to an Excel worksheet and another 1.5 points if a satisfactory report is written.

Next, I went over introductory information: background root information, what is habitat selection, what are the three models, what is the split-root technique? how we can use the split-root technique to determine the habitat selection model of Sugar Ann English peas? I also gave brief instructions on the procedure for today as well as what we are going to do for the remainder of the term. I asked if there were any questions at this time. No one asked a question.

I walked them to the next room to show where the plants would be placed under continuous light. When Student 4 saw the light set-up she said "Wow!" She asked me where I got the materials. I tried to answer the question in an educational way talking about continuous light.

Next, I demonstrated how to make a split-root plant. I opened up a ragdoll and took out one of the plants and pinched off all but two equal roots. I gave students the option to cut the roots with a razor blade or with clean fingernails (Later both students used their fingers not razor blades. If experiment works, may want to change the procedure to only clean fingernails to prevent any accidents with razor blades). I also told them not to use any plants that had a cotyledon with fungal growth or any other contamination. I pointed out an example of what the plant showed look like and told them if any another growth is on the plant then to discard it. (I stressed this point after realizing that last night's class had problems).

I asked students to make as many split-root plants as they could and separate them into containers with water by the length of the split-root: smaller and larger. I explained that they need 16 split-root plants that are roughly the small length size. They could trade with their neighbors until they had the 16 plants. The plants were then set up in fence-sitter or owner scenario. I also demonstrated how to do this.

After 18 minutes (faster the second time), my introductory discussion was over and I announced that it was time to begin.
Student 5 and Student 4 took their ragdolls out of the beakers with water and tried to make split-root plants. Student 5 took them out one at a time while Student 4 took many ragdolls out at a time.

The students work independently and quietly as they fashioned split-roots. Both independently asked me to look at their plants to make sure "they are okay" They were fine. Student 5 asked me if once she had a split-root plant could she trim the roots to equal lengths. I said that no that it would be the same as removing the root and would not work. I also told Student 5. (I forgot to stress that the two approximately equal roots should not be cut).

Student 4 and Student 5 shared their split-root plants until they both had 16 plants about the same size (I was impressed how well they helped out each other and shared their supplies, they were working collaboratively.

They each made 4 fence-sitter and 4 owner scenarios. Both students asked me to make sure they were doing it right. They were. (Since this was new material, they may have been questioning themselves, in addition, they knew that if the scenarios are not set up correctly now they will not have plants or correct data, at this point I am probably seen as an authority instead of a facilitator). The students also used the Velcro strips effectively when staking their plants into position (These strips are great, a must material)

Once, they had fashioned their scenarios, I asked them to transport their plants on a cart to the other room and set up their plants randomly. Student 4 was finished first so she put up her plants. While she was putting up her plants, Student 5 asked me about where to get the Velcro strips. While I answered her, Student 4 packed up her things, said "thanks" and left.

When Student 5 was finished, I went with her to place her plants under the grow light. I saw that Student 4 had placed her plants not in rows with random placement but not in rows, facing all direct directions (I did not properly explain more of a random placement). I showed Student 5 how to place her plants "randomly". She packed up and left.

The class ended at 10:35 p.m.

Notes to self:
- Students worked together well: sharing split-root plants they made.
- Students wanted me to double check when they made the fence-sitter and owner setups.
- Student questions were mainly on the procedure.

Ways to improve:
- Overall, the class seemed to run smoothly, but definitely room for improvement
- Stress that you do not cut the roots of a split-root plant
- I explained how to detect contamination better, however, I did not properly explain random placement. I will make correction in the lab procedure handouts (maybe a picture, information for students, and help to remind me)

Appendix L

Objectivist- Teaching Student Evaluation Results

Evaluation for Extra Credit Medicinal Botany Project

Directions: Neither Shannon Elliott nor Dr. Fox will view the results of your evaluation until grades for this project are recorded. Please check the box (agree, neutral, or disagree) that best applies to the following questions regarding this opportunity.

Questions Regarding the Extra Credit Opportunity	Agree	Neutral	Disagree
Were the instructions easy to follow?	5 (100%)	0 (0%)	0 (0%)
Are the handouts on elearning.uwf.edu helpful?	5 (100%)	0 (0%)	0 (0%)
Do you know more about plant habitat selection now than before this opportunity?	5 (100%)	0 (0%)	0 (0%)
Did you employ critical thought in this experiment?	2 (40%)	3 (60%)	0 (0%)
Were some parts of your learning self-guided?	3 (60%)	2 (40%)	0 (0%)
Would you have preferred to work as a group instead of individually?	0 (0%)	1 (20%)	4 (80%)
Did you view the teacher as more of an authoritative figure? -OR-	4 (80%)	1 (20%)	0 (0%)
Did you view the teacher more as a coach or facilitator?	0 (0%)	1 (20%)	4 (80%)
When you had a question was your first response to ask the teacher? -OR-	5 (100%)	0 (0%)	0 (0%)
When you had a question was your first response to ask a classmate?	0 (0%)	0 (0%)	5 (100%)
Could you explain this experiment and your results to a friend?	5 (100%)	0 (0%)	0 (0%)
Would you recommend this extra credit opportunity to a friend?	5 (100%)	0 (0%)	0 (0%)

What aspect of this experiment did you like?

Student a	I found it very interesting on how fast the pea plants grew. I also enjoyed how this has been very easy to follow experiment
Student b	The ability to see plant grow using experimentation with fast results.
Student c	The ease of how it was performed
Student d	Learning how to care for plants (i.e. staking, etc) and how to make an experiment consistent
Student e	The hands on experience, taking care of the plant, simplicity of the experiment, easy to follow

What aspect of this experiment could be improved?

Student a	Nothing I can think of
Student b	Have more hands available, i.e. group work.
Student c	Nothing. It was a very nice and easy experiment to do
Student d	The rinsing of vermiculite was fairly difficult- do it together
Student e	The weighing process could be a group effort

Would you be able to design an experiment that tests habitat selection using the split-root technique, like our fence-sitters versus owners experience?

If you can think of one, please write or draw it below:

Student a	I can't think of one
Student b	No
Student c	Blank
Student d	Blank
Student e	Blank

What would you expect for Sugar Ann English peas, if one root of a split-root pea experiences twice as much nutrients as the other root? Does competition play a role?

Student a	No, the peas do not care about competition, only the resources available.
Student b	No, because the nutrients are still available for the plant to use
Student c	Nothing really. The plant would grow just as fine. Competition would not play a role
Student d	No. Sugar Ann English peas do not show competition, but resource matching meaning they are concerned with the amounts of nutrients they receive.
Student e	The plant experiencing more nutrients would have better growth.

Appendix M

Constructivist- Teaching Group Designs

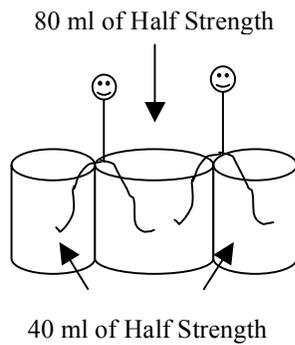| Group #	Drawing	Null and Alterative Hypotheses and Statistical Test
One	Half Strength 80 ml per plant Quarter Strength 80 ml per plant	**Hypotheses for Roots:** H_o: There is no effect of space on the mean weight of roots of fence-sitters and owners. H_a: There is an effect of space on the mean weight of roots of fence-sitters and owners H_o: There is no effect of nutrients on the mean weight of roots of fence-sitters and owners. H_a: There is an effect of nutrients on the mean weight of roots of fence-sitters and owners H_o: There is no interaction of space and nutrients on the mean weight of roots of fence-sitters and owners. H_a: There is interaction of space and nutrients on the mean weight of roots of fence-sitters and owners. **Hypotheses for Shoots and Fruits:** Concerning the shoots, the same null and alternative hypotheses above but replace "roots" with "shoots." For fruits, replace "roots" with "fruits" for the three above null and corresponding alternative hypotheses. **Test:** A Two-Factor ANOVA is run for each of the following: roots, shoots, and fruits.
Two	Full Strength Half Strength 80 ml per plant	**Hypotheses:** H_o: Mean of the root, shoot, and fruit weights for fence-sitters receiving full strength = Mean of the root, shoot, and fruit weights for fence-sitters receiving half strength H_a: Mean of at least one plant organ for fence-sitter receiving full strength $\neq$ Mean of same plant organ for fence-sitter receiving half strength **Test:** Hotelling's T^2 Test
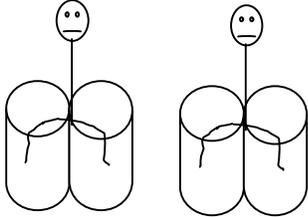
Three	Hypotheses:

80 ml of Half Strength

40 ml of Half Strength

Hypotheses:

H_o: Mean weight of 2 roots in competition (larger pot) = Mean weight of 2 roots not experiencing competition (two smaller pots)

H_a: Mean weight of 2 roots in competition ≠ Mean weight of 2 roots not experiencing competition

Test:

Paired *t*-test

Four
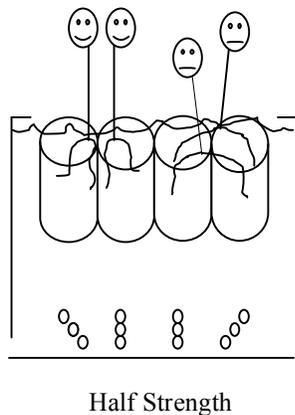
Half Strength

Hypotheses:

H_o: Mean of the root, shoot, and fruit weights for fence-sitters = Mean of the root, shoot, and fruit weights for owners

H_a: Mean of the root, shoot, and/or fruit weights for fence-sitters ≠ Mean of the same dry weight for owners

Test:

Hotelling's T^2 test

Five
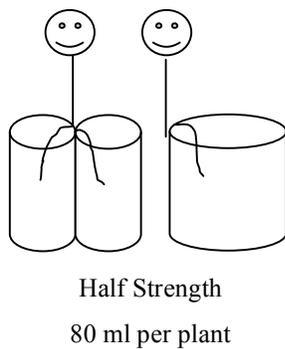
Half Strength

80 ml per plant

Hypotheses:

H_o: Mean of the root, shoot, and fruit weights for fence-sitters = Mean of the root, shoot, and fruit weights for single-root plants

H_a: Mean of the root, shoot, and/or fruit weights for fence-sitters ≠ Mean of the same dry weight for single-root plants

Test:

Hotelling's T^2 test

Note: Full, half, and quarter strength refer to concentrations of Hoagland's medium (Hoagland & Arnon, 1950).

Appendix N

Constructivist- Teaching Fieldnotes Sample

Date: Monday, August 28, 2006
Time: 4:00-6:20
Setting: UWF, Building 58A, Room 210
Class: Plant Biotechnology Lab

Objectives of the class on this day:
Dr. Fox will present the syllabus, lab safety, and experimental flowchart.
Dr. Fox will ask the class to divide into 5 groups.
I will introduce the topic of habitat selection, outline weeks1-11 and ask them in groups
to design an experiment to test the habitat selection model of peas.

Before lab, I tested the projector with my laptop to make sure that my PowerPoint would
work. I talked through the PowerPoint to myself twice and set the projector and laptop to
the side.

The lab is composed of a teacher's desk at the front facing three long benches that each
have a seat for 8 students. Bench 1 is closest to the door that leads to the greenhouse
while Bench 2 is in the middle with Bench 3 the first bench that students reach when they
enter either two doors from the hallway. There are also two long benches: one to the side
of Bench 1 and the other one is behind the rear of all benches (see set-up). In the nook
between the back benches is a computer.

At 4:00, there are 22 students in the class with each bench filled except for the last 2 sets
on Bench 1. Dr. Fox is sitting by the computer as well Allyson Bradley (TA). I am
sitting at the bench parallel to Bench 1. Allyson has passed out a packet to each student
that contains: lab syllabus, background information, experimental flowchart, my habitat
selection model handouts, and molecular handouts.

Dr. Fox starts the class by first giving introductions and touching on the syllabus. He
also goes over lab safety and the layout of the lab while finishing with the experimental
flowchart. For the first 11 weeks the following is the plan

Habitat Selection Model of Peas
Experimental Flow Chart

Week	Left column	Right column
Week 3 Sep 11	Plant seeds in ragdolls / Decide scenarios to test	
Week 4 Sep 18	Cut distal ends of radicles	Harvest tissue
Week 5 Sep 25	Make split root plants & set up scenarios	Protein Isolation
Week 6 Oct 2	Make measurements on plant scenarios	1st dimension of 2D-Gel / RNA extraction
Week 7 Oct 9	Make measurements on plant scenarios	2nd dimension of 2D-Gel (some) / RNA gel / Protein & NA quantification
Week 8 Oct 16	Make measurements on plant scenarios	2nd dimension of 2D-Gel (some) / Polyribosome isolation
	TA weighs crucibles	
Week 9 Oct 23	Make measurements on plant scenarios & harvest tissue	Polyribosome Isolation / Harvest tissue
	TA weighs samples & does statistics	
Week 10 Oct 30	Discuss data	Protein & RNA isolations
Week 11 Nov 6		RNA & SDS-PAGE gels

He asks the class to break into 5 groups and put the names of each member on the board, which has written "Group 1", "Group 2", "Group 3", "Group 4", and "Group 5" *(gives me time to set up my laptop and projector)*. The students quickly form groups and write their names on the board. *(students form groups with neighbors, groups picked based on location, let's see how this works out, groups members coded)*

(One person came in during Dr. Fox's talk, Although group 4 only has 3 people, 2 other people have signed up for the class and will be added to group 4).

Next I begin my PowerPoint presentation which includes
- background information on habitat selection including definitions and three models of habitat selection
- relevance of studying the habitat selection model
- our question that we will answer in groups "Which habitat selection model do Sugar Ann English peas employ?"
- our process-forming groups, making own design

- split-root technique
- example=fence-sitter v owner
- how to create your group design
- what we are going to do for the next 11 weeks

With the laptop and projector, I showed them my site I had make of video and audio recordings of me performing the fence-sitter v owner example. I asked them to look over week 1 (how to plant ragdolls) and read over the journal article by the next class period. I finished by telling them that as a group they can start to work on their design or decide as a group to brainstorm individually and share next time. Either way they knew by the end of the next period they had to have their plan (*I was curious what the group would do*).

Then I passed out the consent form and discussed what they were signing and that they would receive a copy. They all filled out the form and returned it to me. *(Great! no problems)*

After this, the students were allowed to proceed as they wish. All members in Group 1 stayed to talk about the design as well as the five members in Group 5 and one member in Group 4. Groups 2 and 3 made plans to brainstorm individually and discuss next time.

While several groups discussed ideas, group 4 immediately asked to use the hydroponic apparatus to do the fence-sitter versus owner experiment. I discussed the setup with one group member the lighting, medium, air system, etc. (*member seemed to understand by gestures and facial expressions, smiling, nodding, "yes"*) The member asked about randomization (*graduate student graduate thinking*) and I discussed a possible plan for his group.

Next, I asked them how brainstorming was going for group 4. One member showed that they had several drawings with fence-sitters arranged in different ways and presented a specific design of a fence-sitter versus a single-root plant. However, the same member said they did not know what to do from there. I questioned them about how they might treat each group. A fourth member said how about treating them the same with the same nutrients. I asked them what would be the null and alternative hypotheses to this design? I said I would be back for their response (*they are working well as a group, brainstorming, thinking of ideas*)

I went over to Group 1 to see what they were up to. Several members were flipping through the fence-sitter v owner article and individually had drawings in front of them (*thinking independently*). One member (student 1-1) said the only design you could do is the fence-sitter versus owner design. (*seemed frustrated*). Two other members (students 1-2, 1-3) shook through heads in agreement (*following the other's lead*). Student 1-4 presented a design two fence-sitters with one roots sharing a space. I said that they could try this design. Student 1-1 said that they all wanted to think about it (*seems to be competing with group*). Student 1-2 that previously shook his head yes suggested that

they meet after lecture tomorrow at talk. Student 1-1 said that he wanted the extra time to research and think (*acting as the leader, I am surprised that they did not go with the design presented by student 1-4, competition).*

When I returned to Group 5, they had written notes about the null and alternative hypotheses. One student (5-2) presented their design with the appropriate hypotheses. They asked me if their design was okay. I told them their design seemed fine and was excited to see what unfolds. One student writes down their design and gives me a copy (*good design, good interaction between members, they are working together and helping each other, constructivism in action*).

Group 1 left. I asked student 1-1 what they group are going to do. Student 1-1 said they are going to meet after lecture class.

Group 4 remaining members and 5 have left also.

I put up the projector and laptop and locked them up (*I am excited about Groups 4 and 5 and am slightly confused about Group 1. I am looking forward to what groups 2 and 3 design)*

Notes:
Members of 3 groups stayed to work on design
In Groups 1 and 5 students presenting ideas and discussing them over
Group 1 could have had a design but wanted to think it over, competition?
Group 4 decides on hydroponic design
Group 5 wanted me to read over their design before they left
Leader in group 1 and 4 emerges, working together well in Group 5
Groups 2 and 3 left after saying would think of deigns individually and discuss next time (curious to see how unfolds)

Trends:
Several groups concerned about their design
Group leaders are emerging
Competition versus collaboration
Individual plan versus initial group plan
Questions mainly among members, but many directed toward me, will this continue?

Appendix O

Constructivist- Teaching Student Evaluation Results

Evaluation for Habitat Selection Experiment (Plant Biotechnology Lab)

Directions: Shannon Elliott nor Dr. Fox will view the results of your evaluation until grades for this project are recorded. Please check the box (agree, neutral, or disagree) that best applies to the following questions regarding this opportunity.

Questions Regarding the Extra Credit Opportunity	Agree	Neutral	Disagree
Were the instructions easy to follow?	20 (90.9%)	2 (9.1%)	0 (0%)
Are the handouts on elearning.uwf.edu helpful? **1 blank (4.5%)**	16 (72.7%)	5 (22.7%)	0 (0%)
Do you know more about plant habitat selection now than before this opportunity**? 1 blank (4.5%)**	19 (86.4%)	2 (9.1%)	0 (0%)
Did you employ critical thought in this experiment?	16 (72.7%)	5 (22.7%)	1 (4.5%)
Were some parts of your learning self-guided?	13 (59.1%)	7 (31.8%)	2 (9.1%)
Would you have preferred to work individually instead of a group?	5 (22.7%)	1 (4.5%)	16 (72.7%)
Did you view the teacher (Shannon) as more of an authoritative figure? **(4 blank but 3 of the 4 say agree with coach) (18.2%)**	2 (9.1%)	4 (18.2%)	12 (54.5%)
-OR- Did you view the teacher (Shannon) more as a coach or facilitator? **(3 blank 2 of 3 neutral for figure) (13.6%)**	15 (68.2%)	4 (18.2%)	0 (0%)
When you had a question was your first response to ask the teacher? **(2 blank: the 2 had agree for classmate) (9.1%)**	13 (59.1%)	1 (4.5%)	6 (27.3%)
-OR- When you had a question was your first response to ask a classmate? **(4 blank: the 4 had agree for teacher) (18.2%)**	8 (36.4%)	6 (27.3%)	4 (18.2%)
Could you explain this experiment and your results to a friend?	20 (90.9%)	1 (4.5%)	1 (4.5%)
Would you recommend this experience to a friend?	19 (86.4%)	2 (9.1%)	1 (4.5%)

What aspect of this experiment did you like?
Students
    a) Using scientific techniques in everyday applications
    b) Working as a group
    c) I enjoyed measuring all the plants each week to <u>visually</u> see how they were changing
    d) Group work
    e) Loved measuring and observing the plants each week. I am more of a "hands-on" explorer. It was a lot of fun. I also enjoyed presenting/resolving evidence with a conclusion of hypothesis.
    f) The formulations of the ideal setup under specific conditions before we start the experiment and plant the seeds
    g) I liked the teamwork. And also working with the cutie little pea plants
    h) Working with a group towards a common goal
    i) I liked that we could work in groups and help each other out
    j) Being able to go through the whole process of designing an experiment, running the test, and evaluating the results
    k) Seeing the growth trend was aspect that I liked the most. Leaves and tendrils showed a linear relationship, height showed a logarithmic progression, fruits and flowers showed an exponential progression
    l) Working in groups
    m) Blank
    n) The molecular parts
    o) Doing the experiment, designing and collecting data
    p) Blank
    q) The simplicity of it
    r) I liked designing the experiment
    s) Molecular techniques
    t) Being able to come up with our own experimental design
    u) Blank
    v) I liked to watch the plants grow, and the anticipation of finding out the results

Notes:
Blank: 3 (13.6%)
Group work: 6 (27.3%)
Growing plants: 4 (18.2%)
Designing experiment: 6 (27.3%)
Molecular parts: 2 (9.1%)
Other: 1 (4.5%)
The simplicity of it

What aspect of this experiment could be improved?
Students
    a) Blank
    b) Time, equipment used
    c) I felt that the lab went smoothly all-around; therefore, I don't see any need for improvement
    d) Length of time (Make longer)
    e) I hope that through our design actually helped part of Shannon's research. If not, she could present scientific designs to be tested
    f) Maybe the students could be more worked into taking care of the plants so they could follow the development not just once a week. Maybe we can try another seed type too.
    g) More background on past similar experiments
    h) Be able to grow plants longer than 4 weeks
    i) I would like to extend the amount of time the experiment was carried out for
    j) Blank
    k) Blank
    l) Needed more time
    m) Blank
    n) Blank
    o) Working in a group
    p) Group work is torture!
    q) More growing time. Maybe 1 to 2 more weeks
    r) It would have been nice to do experiments which would have shown more graduations of plant growth
    s) I think it was a well written experience
    t) Blank
    u) Blank
    v) More information about the experiment as a whole

Notes:
Blank: 7 (31.8%)
No improvements: 3 (13.6%)
More time/longer experiment: 6 (27.3%)
More background info: 2 (9.1%)
Group Work: 2 (9.1%)
Other: 2 (9.1%)
It would have been nice to do experiments which would have shown more graduations of plant growth
Responsible for taking care of plants/ another seed type

Would you be able to design another experiment that tests habitat selection using the split-root technique?

If you can think of one, please write or draw it below:

Students:
a) Blank
b) Yes
c) Yes (drawing of a fence-sitter (vary the light and nutrient conditions) and drawing of two owners in one pot (see how the plant do in intra-plant avoidance response-measure the competition)
d) Yes
e) Yes (drawing of fence-sitter (vary concentrations of nutrients) and drawing of two owners in two different pots)
f) Maybe we can make use of another variable to affect the final result. Can plant outside under different resource conditions (spring vs. fall, winter, vs. summer) Or try to use some kind of external factor such as predation or symbiosis relating to habitat selection
g) Yes (drawing of two fence-sitters sharing a space plus a control group
h) Blank
i) Blank
j) Blank
k) Blank
l) Needed more time
m) Blank
n) Blank
o) Blank
p) Blank
q) Yes (drawing of fence-sitter half versus full strength)
r) (Drawing of a plant experiencing extreme competition versus one with no competitors)
s) Yes (drawing of two owners versus fence-sitters with varying space)
t) Yes (Fence-sitter with a split-root in one pot, drawing of split-root and owner)
u) Blank
v) Yes (drawing of 3 fence-sitters sharing three spaces)

<u>Notes:</u>
Blank: 10 (45.5%)
Yes: 2 (9.1%)
Yes with drawing or description: 9 (40.9%)
Other: 1 (4.5%)
Needed more time

Based on what you know about the habitat selection model of Sugar Ann English peas, what light, spacing, and nutrient considerations would you make if planting them in a garden? Does competition from another plant play a role?

Students
a) I would plant them about 5 inches apart in full sun in soil. They don't seem to need special nutrients
b) Yes, how much direct sunlight would be received, enough space so that the roots wouldn't get tangled
c) In a garden, I would make sure there is a great deal of spacing between the plants. The nutrients would be kept relatively the same for all the plants. There needs to be lighting for them (peas), but it would vary.
d) No, resource matching. Equal amounts=optimal growth, trend in growth indicated intra-plant avoidance, fence-sitters=more successful
e) Nutrition is the growth limiting factor. Consistent light and certain amount of space is required.
f) I would plant in a light space, with enough constant food (nutrition), and with random and good interspersion between them. Maybe not plant close to other species so competition (inter) doesn't affect.
g) The peas need to be planted in an area where they will get a good amount of light. It doesn't really matter how close together they are planted, but they do like a nutrient rich environment.
h) Intra-plant avoidance seemed like what we would have observed based on trends, fence-sitters probably would be more successful
i) Based on what we know in the time period we observed the plants were resource-matching, but if we could have let them grow a little longer we may have found that there was a trend for intra-plant avoidance.
j) Blank
k) Blank
l) Like light, need nutrients
m) Blank
n) Blank
o) Blank
p) Statistically, almost nothing can be concluded from any of the group's experiments. It looks like they are basic resource-matching plants
q) They could get all of the nutrients they needed. My group didn't test that.
r) I would plant them all together because they are resource matching
s) Yes, if there's not enough nutrients, add light, water and nutrients
t) I would plant them in full to partial light spaced about 3 inches apart changing the soil once or twice a year to replenish nutrients. We did not test to see if the peas compete with other species but based on experiment we did in class find the pea plants are resource matching
u) Blank

v) I know that in order to flower they have to be planted at the right time to get the light cycles right. The plants around them don't affect them and they can adapt to a reasonable amount of nutrients.

Notes:
Blank: 6 (27.3%)
Mentioned resource matching: 6 (27.3%)
Nutrients the same: 8 (36.4%)
Competition with other plants: 2 (9.1%)

***Thank you for your evaluation. Your advice will be utilized to improve this experiment! ***