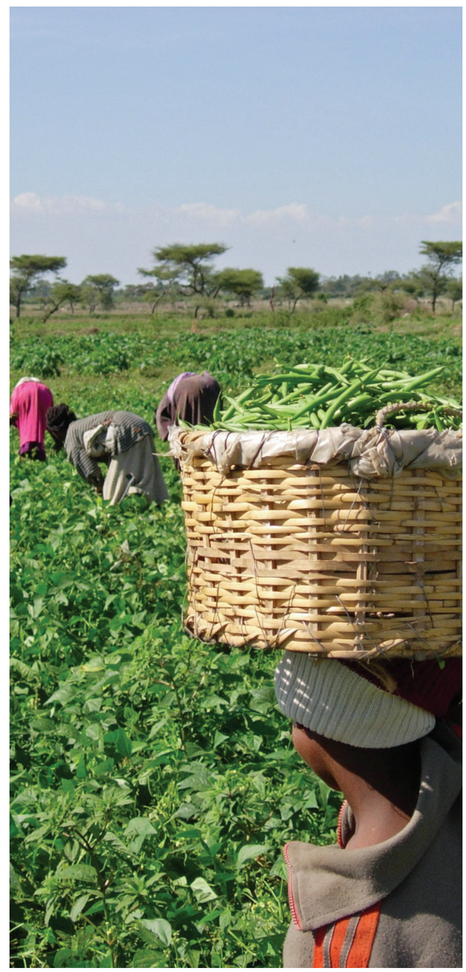
Plant Science Classroom Material for High Schools in Ontario

Nourishing the Planet in the 21st Century

High School Science Module





NUTRIENTS FOR LIFE

Nourishing the Planet in the 21st Century

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Preface:

Focus: Nutrients for Life Foundation Canada

Nourishing the Planet in the 21st Century is a teaching tool aimed at helping teachers and students explore one central issue:

How can we ensure that the earth's growing population can be fed sustainably in the coming decades?

This complex question could lead to a very broad exploration of many social, environmental, scientific and ethical questions.

The UN Food and Agriculture Organization (FAO) has identified the key elements of stewardship in their release on December 10, 2007, Rome; Dr. Jacques Diouf, FAO Director-General stated, "The key elements in feeding the world now and in the future will be increased public and private investments, the right policies and technologies, knowledge and capacity building, grounded in sound ecosystem management." He added that "There is no one solution to the problem of feeding the world's hungry and poor".

In keeping with Nutrients for Life's mandate, we are focusing our attention on one significant aspect of these issues:

How to understand the science of plant biology as it relates to food production.

This material also weaves in some elements of the social and environmental issues connected to the question, but maintains a strong focus on the science aspects related to the central question of feeding an increasingly hungry world. We acknowledge that there are a broader range of elements that might be linked to this issue and we would encourage teachers to supplement this material from additional sources in areas where they wish to expand the social and environmental debates.

A Word on Stewardship

Canadian law defines the term 'fertilizer' in the Fertilizers Act:

> "Fertilizer" means any substance or mixture of substances, containing nitrogen, phosphorus, potassium or other plant food, manufactured, sold or represented for use as a plant nutrient…"

In order to avoid misinterpretation, Nutrients for Life has, in the curriculum resources, replaced the generic use of the term "fertilizer" with "plant nutrients" or "crop nutrients" unless the source is specifically identified – as, for example, "manure". In these reference materials the term "plant nutrients" will be used to refer to the generic context; commercial, mineral, or inorganic fertilizers will be used to identify all manufactured and mined sources of nutrients; and organic fertilizer sources will include biosolids, manures, compost, legumes and green manure crops, etc.

The Foundation advocates the judicious use of all plant nutrients – their application at the right time of the growing season, in the appropriate amount and location, is a matter of environmental stewardship and is specifically endorsed by the United Nations' Food and Agricultural Organization (FAO).

The Foundation supports the environmental stewardship of all plant nutrients and our objective is, at all times, to identify the importance of the scientific principles underlying agriculture and food production.

Nourishing the Planet in the 21st Century

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Introduction

During the past 50 years, the population of Earth has more than doubled, yet the amount of land devoted to farming has stayed about the same. During the same time, the developed world has seen impressive gains in agricultural productivity. This so-called Green Revolution saw farmers in North America produce 300 to 400 percent more food from essentially the same land that was cultivated in 1960. These increased yields have saved over 50 million square kilometres of land from being ploughed. This represents a great deal of land that can be used for other purposes.[6]

Farmers were able to increase their crop yields by growing improved plant varieties, adopting better water management practices, and using supplemental nutrient sources such as manures, composts, and commercial fertilizers more wisely. Nutrient management practices that ensure that needed plant minerals are used at the right time, applied in the proper amount, and placed where the plant can most easily use them play a large role in increasing crop production while minimizing nutrient losses to the environment. At least 40 percent of the world's present food supply is directly attributable to the use of supplemental fertilization that replaces nutrients in the soil that have been removed through farming and the consumption of food away from the farm.

It is estimated that Earth will hold 8 to 9 billion people by 2050.[29] How will we feed all these additional people? In the developed world, the increases in plant productivity supported by the Green Revolution are reaching their potentials. At the same time, and a world away, infrastructure and population growth pressures are forcing farmers in sub-Saharan Africa to grow crop after crop, "mining," or depleting, the soil of nutrients while unable to add additional sources of nutrients. With little access to supplemental nutrients, the farmers are forced to bring less-fertile soils on marginal land into production, at the expense of Africa's wildlife and forests.

Many Canadians are generations removed from the farm and take their food supply for granted. They want their food to taste good, to be reasonably priced, and to be healthy and nutritious. At the same time, they want agricultural systems to be truly sustainable by protecting the environment and setting aside land for wildlife.

Difficult decisions will have to be made. Making more land available for farming also means having less land available for other uses such as housing, recreation, and wildlife habitats. Agricultural practices, if not carried out properly, can harm the environment by introducing excessive amounts of nutrients into rivers, lakes, and coastal waters. In agriculture, as in many other industries, farmer experience and scientific research has helped determine the best management practices -- practices that ensure efficient use of resources and minimize impacts on the environment. The UN FAO has identified the framework for the judicious management of all crop inputs in their release December 10, 2007, Rome; Dr. Jacques Diouf, FAO Director-General, "You have to choose the right inputs, right amounts, and apply them in the right way and at the right time." This framework enables profitability for farmers while guarding the public interest.

The public needs to have a voice in setting policies that affect how the world's food is produced. To make rational decisions about these matters, the world's citizens need to recognize what options are available. Today's young people need to recognize the economic, social, and environmental consequences of the options they will confront as adults facing the challenge of nourishing Earth's growing population.

What Are the Objectives of the Module?

Nourishing the Planet in the 21st Century has four objectives. The first is to help students understand some basic aspects of plant biology related to food production. Although school curricula address plant biology and food production, they usually focus on promoting an understanding of photosynthesis. The importance of protecting the soil and maintaining plant nutrition as it relates to food production is often not explored.

The second objective is to provide students with an opportunity to practice and refine their critical-thinking skills. Such abilities are important, not just for scientific pursuits, but for making decisions in everyday life. Our fast-changing world requires today's young people to be lifelong learners. They must be able to evaluate information from a variety of sources and assess its usefulness. They need to discriminate between objective, accurate information, and biased, sometimes misleading information and they must learn to recognize how gaps or omissions in their information base can also impact their ability to make rational decisions. Students must be able to use evidence to establish causal relationships.

The third objective is to convey to students the purpose of methods of scientific research. Ongoing research affects how we understand the world around us and provides a foundation for improving our choices about personal health and the health of our community, including our environment. In this module, students participate in activities that give them experience with the major aspects of scientific inquiry. The lessons encourage students to think about the relationships among knowledge, choice, behaviour, and human health in this way:

knowledge* (what is known and not known) + *choice* = *power

power* + *behaviour* = *enhanced human health

The final objective of this module is to encourage students to think in terms of these relationships now and as they grow older.

Why Teach the Module?

High school biology classes offer an ideal setting for integrating many areas of student interest. In this module, students participate in activities that integrate inquiry science, plant biology, and mathematics to meet module outcomes. The lessons interweave science, technology, and selected societal issues. The real-life context of the module's classroom lessons is engaging, and the knowledge gained can be applied immediately to students' lives.

What's in It for the Teacher?

Nourishing the Planet in the 21st Century meets many of the criteria by which teachers and their programs are assessed:

- The module is *standards based* and meets relevant provincial science curriculum outcomes.[20,21] It pays particular attention to the outcomes that describe what students should know and be able to do with respect to *scientific inquiry*.
- It is an *integrated* module, drawing most heavily from the subjects of science, social science, mathematics, and health.

In addition, the module provides a means for *professional development*. Teachers can engage in new and different teaching practices such as those described in this module without completely overhauling their entire program. In *Designing Professional Development for Teachers of Science and Mathematics,* Loucks-Horsley, Hewson, Love, and Stiles write that supplements such as this one "offer a window through which teachers get a glimpse of what new teaching strategies look like in action." The use of this kind of supplemental module can encourage reflection and discussion and stimulate teachers to improve their practices by focusing on student learning through inquiry.

Implementing the Module

The six lessons of this module are designed to be taught in sequence over seven to eight days (as a supplement to the standard curriculum) or as individual lessons that support and enhance your treatment of specific concepts in high school biology. This section offers general suggestions about using these materials in the classroom. You will find specific suggestions in the procedures provided for each lesson.

What Are the Goals of the Module?

Nourishing the Planet in the 21st Century helps students achieve four major goals associated with scientific literacy:

- to understand a set of basic elements related to food production,
- to experience the process of scientific inquiry and develop an enhanced understanding of the nature and methods of science,
- to hone critical-thinking skills, and
- to recognize the role of science in society and the relationship between basic science and human health.

What Are the Science Concepts and How Are They Connected?

The lessons are organized into a conceptual framework that allows students to move from what they already know about agriculture, or think they know, to gaining a more complete and accurate perspective on the topic. Students begin by comparing and contrasting the nutritional needs of plants and people (Lesson 1, *In Search of Essential Nutrients*). They then explore soils and investigate how they differ chemically and physically, especially with regard to supporting plant growth (Lesson 2, *Properties of Soils*). Students then turn their attention to plant anatomy. They explore the role of the root system as well as that of the xylem and phloem tissues. They conduct a hands-on activity that shows how nutrients move by diffusion (Lesson 3, *Plant-Soil Interactions*). Students consider what happens when plants do not get adequate amounts of their essential nutrients. They play the role of plant doctor diagnosing the cause of a nutrient deficiency (Lesson 4, *Plant Nutrient Deficiencies*). Students then consider the role of mineral fertilizers and

other nutrient sources in a global context. They investigate how nutrients can be applied to improve crop growth, and help feed people while protecting the environment. The consequences of misusing nutrient applications are also considered (Lesson 5, *Fertilizers and the Environment*). The module concludes with students reflecting on what they have learned about plant biology, supplemental nutrients from organic and commercial fertilizer sources, and the downstream environmental effects of nutrient management in the context of making recommendations for agricultural practices for the future (Lesson 6: *Nourishing the Planet in the 21st Century*). Table 1 illustrates the scientific content and conceptual flow of the lessons.

Table 1.
Science Content and Conceptual Flow of the Lessons

Lesson and Learning Focus*	Topics Addressed and Major Concepts
1: In Search of Essential Nutrients *Engage:* Students become engaged in how plants obtain their nutrition.	Plants and people require essential nutrients to complete their life cycles. Macronutrients are needed in larger amounts than micronutrients. Plants get their nutrients from water, air, and soil.
2: Properties of Soils *Explore:* Students consider what makes one soil better able to support plant growth as compared with another.	Soils vary with regard to the amount of organic and inorganic matter they contain. Some soils hold and transmit water better than others. Plants take up whatever is dissolved in soil water.
3: Plant-Soil Interactions *Explain:* Students conduct observations and experiments to investigate how plants obtain nutrients from the soil.	Plants extract nutrients from the soil. Nutrients move in the soil by mass flow or diffusion and are absorbed into the root system.. Water and photosynthesis produced products are transported within the plant by the use of the xylem and phloem tissues respectively.
4: Plant Nutrient Deficiencies *Elaborate:* Students deepen their understanding of the nutritional requirements of plants by diagnosing plant nutrient deficiencies.	Crop plants with nutrient deficiencies show specific symptoms. These deficiencies can be corrected by using nutrient sources that restore nutrient balance to the soil.
5: Supplemental Nutrient Sources and the Environment *Explain-Elaborate:* Students apply their understanding of nutrient management to a global scale and consider how adding nutrients affects the environment.	Adding nutrients from bio-solids or commercial fertilizer sources can increase the amount of food and fibre produced per hectare thereby reducing the amount of land needed for farming. Our growing population demands that more food be produced. Unless crop yields keep pace with the demand, more land will have to be converted over to agricultural production.
6: Nourishing the Planet in the 21st Century *Evaluate:* Students apply what they learned during the module to make recommendations for how to nourish the Earth's increasing population.	Human population growth challenges us to implement farming practices that can meet our nutritional needs while at the same time minimizing negative impacts such as nutrient run-off, erosion, and excessive land use.

*See How Does the BSCS 5E Instructional Model Promote Active, Collaborative, Inquiry-Based Learning?

What the Module Does Not Cover

The lessons are focused on plant nutrients in the context of agriculture. Some of the generalizations in the module apply equally well to crop and non-crop plant species, but in many cases they do not apply to non-crop species and non-agricultural ecosystems. For the purpose of this module, we define crop species broadly, as food crops, lawns, garden and ornamental plants such as flowers.

In keeping with our stated focus on understanding the science of plant biology as it pertains to feeding the planet, we have been careful to respect the boundary around what we can and cannot realistically address in this module.

There are related issues the module does not address in detail. These include the complex effects of nutrient enrichment on non-managed land ecosystems such as forests, wetlands, deserts and grasslands; the important role that crop management plays in reducing nutrient loss to the environment, such as the merits of planting cover crops (i.e. crops that are not planted to be harvested, but are used to protect the soil, and absorb nutrients susceptible to losses); and the influence of soil management practices on nutrient losses to the environment, such as using buried drain pipes to rapidly remove water from agricultural fields. The module also limits its environmental impacts/benefits focus to the downstream effects of all types of supplemental plant nutrients. Issues associated with the production of organic or commercial fertilizers are not addressed.

How Does the Module Correlate with Ontario Grades 9-12 Science Curricula?

Nourishing the Planet in the 21st Century supports teachers in their efforts to implement relevant Ontario Grades 9-12 Science curriculum expectations. Table 2 lists specific expectations that this module addresses.

Table 2.
Correlation of Ontario Grades 9-12 Science Curriculum Expectations to *Nourishing the Planet in the 21st Century*

Relevant Ontario Grades 9-12 Science Curriculum Expectations	Corresponding *Nourishing the Planet in the 21st Century* Lessons
Relating Science and Technology to Society and the Environment	
■ Assess the environmental implications of food choices available in a variety of situations (*e.g., in the school cafeteria, a fast-food restaurant, a supermarket, a local farmers' market, an organic meat shop*), and propose ways to minimize the environmental impact of their food choices	Lesson 4, 6
■ Analyse the impact of various lifestyle choices on human health and body systems	Lesson 4
■ Assess, on the basis of research, the impact of a factor related to human activity (*e.g., urban sprawl, introduction of invasive species, overhunting/overfishing*) that threatens the sustainability of a terrestrial or aquatic ecosystem.	Lesson 5, 6

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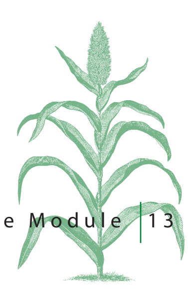

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■ Analyse some of the risks and benefits of human intervention (*e.g., tree plantations; monoculture of livestock or agricultural crops; overharvesting of wild plants for medicinal purposes; using pesticides to control pests; suppression of wild fires*) to the biodiversity of aquatic or terrestrial ecosystems.	Lesson 5, 6
■ Analyse ways in which societal needs or demands have influenced scientific endeavours related to the environment (*e.g., the development of drought- and pest-resistant crops to address the rising global need for food*).	Lessons 5, 6
■ Propose possible solutions, on the basis of research, to a current practical environmental problem that is caused, directly or indirectly, by human activities	Lesson 6,
■ Analyse, on the basis of research, how a human activity threatens the sustainability of a terrestrial or aquatic ecosystem.	Lesson 6
■ Assess the positive and negative impact of human activities on the natural balance of plants (*e.g., crop rotation, the use of fertilizers and herbicides, the introduction of new species*).	Lesson 6
■ Assess, on the basis of research, the effectiveness of some Canadian technologies and projects intended to nourish expanding populations (*e.g., the risks and benefits of growing genetically modified canola*)..	Lesson 6
■ Analyse, on the basis of research, some of the social, ethical, and legal implications of biotechnology (*e.g., the bioengineering of animal species, especially those intended for human consumption; the cultivation of transgenic crops; the patenting of life forms; cloning*).	Lesson 6
Developing Investigation and Communication Skills	
■ Select appropriate instruments (*e.g., sampling instruments, laboratory glassware, magnifying lenses, an electroscope*) and materials (*e.g., ebonite rods, star charts, a ball and spring apparatus, pH paper*) for particular inquiries.	Lesson 3
■ Conduct inquiries, controlling some variables, adapting or extending procedures as required, and using standard equipment and materials safely, accurately, and effectively, to collect observations and data.	Lesson 3
■ Investigate the effect of various qualitative factors (*e.g., temperature*) on the rate of diffusion of molecules across a plasma membrane.	Lesson 3
■ Synthesize, analyse, interpret, and evaluate qualitative and/or quantitative data to determine whether the evidence supports or refutes the initial prediction or hypothesis and whether it is consistent with scientific theory; identify sources of bias and/or error; and suggest improvements to the inquiry to reduce the likelihood of error.	Lesson 3
■ Use appropriate numeric, symbolic, and graphic modes of representation, and appropriate units of measurement (*e.g., SI and imperial units*)	Lesson 5

■ Express the results of any calculations involving data accurately and precisely.	Lesson 5
■ Use a research process to investigate environmentally sustainable methods of managing and maintaining healthy and productive agricultural zones and forests.	Lesson 5
■ Formulate scientific questions about observed relationships, ideas, problems, and/or issues, make predictions, and/or formulate hypotheses to focus inquiries or research.	Lesson 6
■ Analyse and interpret qualitative and/or quantitative data to determine whether the evidence supports or refutes the initial prediction or hypothesis, identifying possible sources of error,bias, or uncertainty.	Lesson 6
■ Draw conclusions based on inquiry results and research findings, and justify their conclusions.	Lesson 6
■ Plan and conduct an investigation, involving both inquiry and research, into how a human activity affects soil composition or soil fertility (*e.g., changes to soil composition resulting from the use of different compostable materials, organic or inorganic fertilizers, or pesticides*), and, extrapolating from the data and information gathered, explain the impact of this activity on the sustainability of terrestrial ecosystems.	Lesson 6
Understanding Basic Concepts	
■ Describe the characteristic physical and chemical properties of common elements and compounds.	Lesson 1
■ Explain the relationships between the properties of elements and their position in the periodic table (*e.g., with reference to atomic structure, group, and period*)	Lesson 1
■ Describe the structure of important biochemical compounds.	Lesson 1
■ Explain the concept of the cycling of substances in ecosystems (*e.g., fertilizers made from biosolids leach into ground water or run off into rivers and streams, where the chemicals are absorbed by aquatic life, which is in turn consumed by humans*).	Lesson 1,2,4
■ Identify the earth's four spheres (biosphere, hydrosphere, lithosphere, atmosphere), and describe the relationship that must exist between these spheres if diversity and sustainability are to be maintained.	Lesson 2,4
■ Identify the basic components of soil, water, and air, and describe some of the effects of human activity on soil, water, and air quality.	Lesson 2,5
■ Explain different ecologically sound practices for improving and maintaining soil structure and fertility	Lesson 2
■ Describe the limiting factors of ecosystems (*e.g., nutrients, space, water, energy, predators*), and explain how these factors affect the carrying capacity of an ecosystem.	Lesson 2,5

■ Identify some factors related to human activity that have an impact on ecosystems (*e.g., the use of fertilizers and pesticides; altered shorelines; organic and conventional farming; urban sprawl*), and explain how these factors affect the equilibrium and survival of populations in terrestrial and aquatic ecosystems (*e.g., fertilizers change the fertility of soil, affecting what types of plants can grow in it*).	Lesson 2,5
■ Describe requirements for a balanced diet based on the biochemical and energy needs of the average body, and explain how these requirements might vary among people with different lifestyles (*e.g., young children, the elderly, a person with diabetes, an athlete*).	Lesson 4
■ Explain agricultural techniques and forestry practices that aim to maintain both biodiversity and long-term productivity (*e.g., growing a variety of species, inter-planting crops, planting native and heritage varietals instead of hybrids or transgenic species, saving seeds, maintaining some older trees and snags for animal habitat*).	Lesson 5,6
■ Explain how a change in one population in an aquatic or terrestrial ecosystem can affect the entire hierarchy of living things in that system.	Lesson 5

Source: Ontario Ministry of Education and Training (2008). The Ontario Curriculum Grades 9 and 10: Science (Revised). Toronto: Queen's Printer for Ontario.
Ontario Ministry of Education and Training (2008). The Ontario Curriculum Grades 11 and 12: Science (Revised). Toronto: Queen's Printer for Ontario.

The suggested teaching strategies in all of the lessons support you as you work to meet the curriculum expectations outlined in relevant Ontario Grades 9-12 Science curricula.[20,21]

This module helps science teachers plan an inquiry-based science program by providing short-term objectives for students. It also includes planning tools for teaching the module, such as Table 1, *Science Content and Conceptual Flow of the Lessons* (page 12) and Table 5, *Suggested Timeline* (page 26). You can use this module to update your course of study in response to students' interest. The focus on active, collaborative, and inquiry-based learning in the lessons helps support the development of student understanding and nurtures a community of science learners.

The structure of the lessons enables you to guide and facilitate learning. All the activities encourage and support student inquiry, promote discourse among students, and challenge students to accept and share responsibility for their learning. The use of the BSCS 5E Instructional Model, combined with active, collaborative learning, allows you to respond effectively to students with diverse backgrounds and learning styles. The module is fully annotated, with suggestions for how you can encourage and model the skills of scientific inquiry and foster curiosity, openness to new ideas and data, and scepticism.

How Does the BSCS 5E Instructional Model Promote Active, Collaborative, Inquiry-based Learning?

Because learning does not occur by way of passive absorption, the lessons in this module promote active learning. Students are involved in more than listening and reading. They are developing skills, analyzing and evaluating evidence, experiencing and discussing, and talking to their peers about their own understanding. Students work collaboratively with others to solve problems and plan investigations. Many students find that they learn better when they work with others in a collaborative environment than when they work alone in a competitive environment. When active, collaborative learning is directed toward scientific inquiry, students succeed in making their own discoveries. They ask questions, observe, analyze, explain, draw conclusions, and ask new questions. These inquiry-based experiences include both those that involve students in direct experimentation and those in which students develop explanations through critical and logical thinking.

The viewpoint that students are active thinkers who construct their own understanding from interactions with phenomena, the environment, and other individuals is based on the theory of *constructivism*. A constructivist view of learning recognizes that students need time to

- express their current thinking;
- interact with objects, organisms, substances, and equipment to develop a range of experiences on which to base their thinking;
- reflect on their thinking by writing and expressing themselves and comparing what they think with what others think; and
- make connections between their learning experiences and the real world.

This module provides a built-in structure for creating a constructivist classroom: the BSCS 5E Instructional Model.[8] The 5E Model sequences learning experiences so that students have the opportunity to construct their understanding of a concept over time. The model leads students through five phases of learning that are easily described using words that begin with the letter *E*: Engage, Explore, Explain, Elaborate, and Evaluate. The following paragraphs illustrate how the five Es are implemented across the lessons in this module.

Engage

Students come to learning situations with prior knowledge. This knowledge may or may not be congruent with the concepts presented in this module. The Engage lesson provides the opportunity for teachers to find out what students already know, or think they know, about the topic and concepts to be covered. The Engage lesson in this module, Lesson 1, *In Search of Essential Nutrients*, is designed to

- pique students' curiosity and generate interest,
- determine students' current understanding about nutritional requirements,
- nvite students to raise their own questions about essential elements,
- encourage students to compare their ideas with those of others, and
- enable teachers to assess what students do or do not understand about the stated outcomes of the lesson.

Explore

In the Explore phase of the module, Lesson 2, *Properties of Soils*, students investigate the compositions of soils. Students perform experiments designed to provide a common set of experiences within which they can begin to construct their understanding. Students

- interact with materials and ideas through classroom and small-group discussions;
- acquire a common set of experiences so that they can compare results and ideas with their classmates;
- observe, describe, record, compare, and share their ideas and experiences; and
- express their developing understanding of testable questions and scientific inquiry.

Explain

The Explain lessons (Lesson 3, *Plant-Soil Interactions* and Lesson 5, *Supplemental Nutrients* and the Environment) provide opportunities for students to connect their previous experiences with current learning and to make conceptual sense of the main ideas of the module. This phase also allows for the introduction of formal language, scientific terms, and content information that might make students' previous experiences easier to describe. The Explain lesson encourages students to

- explain concepts and ideas (in their own words) about how applying additional nutrients affect the environment;
- listen to and compare the explanations of others with their own;
- become involved in student-to-student discourse in which they explain their thinking to others and debate their ideas;
- revise their ideas;
- record their ideas and current understanding;
- use labels, terminology, and formal language; and
- compare their current thinking with what they previously thought.

Elaborate

In Elaborate lessons, students apply or extend previously introduced concepts and experiences to new situations. In the Elaborate lessons in this module (Lesson 4, *Plant Nutrient Deficiencies* and Lesson 5, *Supplemental Nutrients and the Environment*), students

- make conceptual connections between new and former experiences, connecting aspects of their plant and soil investigations with their concepts of scientific inquiry;
- connect ideas, solve problems, and apply their understanding to a new situation;
- use scientific terms and descriptions;
- draw reasonable conclusions from evidence and data;
- deepen their understanding of concepts and processes; and
- communicate their understanding to others.

Evaluate

The Evaluate lesson is the final phase of the instructional model, but it only provides a "snapshot" of what the students understand and how far they have come from where they began. In reality, the evaluation of students' conceptual understanding and ability to use skills begins with the Engage lesson and continues throughout each phase of the instructional model. When combined with the students' written work and performance of tasks throughout the module, however, the Evaluate lesson provides a summative assessment of what students know and can do.

The Evaluate lesson in this module, Lesson 6, *Nourishing the Planet in the 21st Century,* provides an opportunity for students to

- demonstrate what they understand about plants and fertilizers and how well they can apply their knowledge to make recommendations for feeding our increasing population,
- defend their recommendations with evidence,
- share their current thinking with others,
- assess their own progress by comparing their current understanding with their prior knowledge, and
- ask questions that take them deeper into a concept.

To review the relationship of the 5E Instructional Model to the concepts presented in the module, see Table 1 (page 12).

When you use the 5E Instructional Model, you engage in practices that are different from those of a traditional teacher. In response, students learn in ways that are different from those they experience in a traditional classroom. The following charts, Table 3, *What the Teacher Does* and Table 4, *What the Students Do*, outline these differences.

Table 3.

What the Teacher Does

Phase	That is Consistent with the 5E Instructional Model	That is *Inconsistent* with the 5E Instructional Model
Engage	■ Piques students' curiosity and generates interest ■ Determines students' current understanding (prior knowledge) of a concept or idea ■ Invites students to express what they think ■ Invites students to raise their own questions	■ Introduces vocabulary ■ Explains concepts ■ Provides definitions and answers ■ Provides closure ■ Discourages students' ideas and questions
Explore	■ Encourages student-to-student interaction ■ Observes and listens to the students as they interact ■ Asks probing questions to help students make sense of their experiences ■ Provides time for students to puzzle through problems	■ Provides answers ■ Proceeds too rapidly for students to make sense of their experiences ■ Provides closure ■ Tells the students that they are wrong ■ Gives information and facts that solve the problem ■ Leads the students step-by-step to a solution
Explain	■ Encourages students to use their common experiences and data from the Engage and Explore lessons to develop explanations ■ Asks questions that help students express understanding and explanations ■ Requests justification (evidence) for students' explanations ■ Provides time for students to compare their ideas with those of others and perhaps to revise their thinking ■ Introduces terminology and alternative explanations after students express their ideas	■ Neglects to solicit students' explanations ■ Ignores data and information students gathered from previous lessons ■ Dismisses students' ideas ■ Accepts explanations that are not supported by evidence ■ Introduces unrelated concepts or skills
Elaborate	■ Focuses students' attention on conceptual connections between new and former experiences ■ Encourages students to use what they have learned to explain a new event or idea ■ Reinforces students' use of scientific terms and descriptions previously introduced ■ Asks questions that help students draw reasonable conclusions from evidence and data	■ Neglects to help students connect new and former experiences ■ Provides definitive answers ■ Tells the students that they are wrong ■ Leads students step-by-step to a solution
Evaluate	■ Observes and records as students demonstrate their understanding of the concepts and performance of skills ■ Provides time for students to compare their ideas with those of others and perhaps to revise their thinking ■ Interviews students as a means of assessing their developing understanding ■ Encourages students to assess their own progress	■ Tests vocabulary words, terms, and isolated facts ■ Introduces new ideas or concepts ■ Creates ambiguity ■ Promotes open-ended discussion unrelated to the concept or skill

Table 4.

What the Students Do

Phase	That Is *Consistent* with the 5E Instructional Model	That Is *Inconsistent* with the 5E Instructional Model
Engage	■ Become interested in and curious about the concept or topic ■ Express current understanding of a concept or idea ■ Raise questions such as, "What do I already know about this?" "What do I want to know about this?" "How could I find out?	■ Ask for the "right" answer ■ Offer the "right" answer ■ Insist on answers or explanations ■ Seek closure
Explore	■ Explore materials and ideas ■ Conduct investigations in which they observe, describe, and record data ■ Try different ways to solve a problem or answer a question ■ Acquire a common set of experiences so that they can compare results and ideas ■ Compare their ideas with those of others	■ Let others do the thinking and exploring (passive involvement) ■ Work quietly with little or no interaction with others (only appropriate when exploring ideas or feelings) ■ Stop with one solution ■ Demand or seek closure
Explain	■ Explain concepts and ideas in their own words ■ Base their explanations on evidence acquired during previous investigations ■ Record their ideas and current understanding ■ Reflect on and perhaps revise their ideas ■ Express their ideas using appropriate scientific language ■ Compare their ideas with what scientists know and understand	■ Propose explanations from "thin air" with no relationship to previous experiences ■ Bring up irrelevant experiences and examples ■ Accept explanations without justification ■ Ignore or dismiss other plausible explanations ■ Propose explanations without evidence to support their ideas
Elaborate	■ Focus their attention on conceptual connections between new and former experiences ■ Use what they have learned to explain a new event or idea ■ Use scientific terms and descriptions previously introduced ■ Answer questions that help them draw reasonable conclusions from evidence and data	■ Ignore previous information or evidence ■ Draw conclusions from "thin air" ■ Use terminology inappropriately and without understanding
Evaluate	■ Make conceptual connections between new and former experiences ■ Use what they have learned to explain a new object, event, organism, or idea ■ Use scientific terms and descriptions ■ Draw reasonable conclusions from evidence and data ■ Communicate their understanding to others ■ Demonstrate what they understand about the concepts and how well they can implement a skill ■ Compare their current thinking with that of others and perhaps revise their ideas ■ Assess their own progress by comparing their current understanding with their prior knowledge ■ Ask new questions that take them deeper into a concept or topic area	■ Disregard evidence or previously accepted explanations in drawing conclusions ■ Offer only yes-or-no answers or memorized definitions or explanations as answers ■ Fail to express satisfactory explanations in their own words ■ Introduce new, irrelevant topics

How Does the Module Support Ongoing Assessment?

Because teachers will use this module in a variety of ways and at a variety of points in their science programs, the most appropriate mechanism for assessing student learning is one that occurs informally at various points within the lessons, rather than just once at the end of the module. Accordingly, integrated within the lessons in the module are specific assessment components. These embedded assessments include one or more of the following strategies:

- Performance-based activities, such as interpreting graphs or participating in a discussion about risks and benefits.
- Oral presentations to the class, such as reporting experimental results.
- Written assignments, such as answering questions or writing about demonstrations.

These strategies allow you to assess a variety of aspects of the learning process such as students' prior knowledge and current understanding, problem-solving and critical-thinking skills, level of understanding of new information, communication skills, and ability to synthesize ideas and apply understanding to a new situation.

How Can Teachers Promote Safety in the Science Classroom?

Even simple science demonstrations and investigations can be hazardous unless teachers and students know and follow safety precautions. Teachers are responsible for providing students with active instruction concerning their conduct and safety in the classroom. Posting rules in a classroom is not enough; teachers also need to provide adequate supervision and advance warning if there are dangers involved in the science investigation. By maintaining equipment in proper working order, teachers ensure a safe environment for students.

You can implement and maintain a safety program in the following ways:

- Provide eye protection for students, teachers, and visitors. Require that everyone participating wear regulation goggles in any situation where there might be splashes, spills, or spattering. Teachers should always wear goggles in such situations.
- Know and follow the provincial and district safety rules and policies. Be sure to fully explain to the students the safety rules they should use in the classroom.
- At the beginning of the school year, establish consequences for students who behave in an unsafe manner. Make these consequences clear to students.
- Do not overlook any violation of a safety practice, no matter how minor. If a rule is broken, take steps to assure that the infraction will not occur a second time.
- Set a good example by observing all safety practices. This includes wearing eye protection during all investigations when eye protection is required for students.

- Know and follow waste disposal regulations.
- Be aware of students who have allergies or other medical conditions that might limit their ability to participate in activities. Consult with the school nurse or school administrator.
- Anticipate potential problems. When planning teacher demonstrations or student investigations, identify potential hazards and safety concerns. Be aware of what could go wrong and what can be done to prevent the worst-case scenario. Before each activity, verbally alert the students to the potential hazards and distribute specific safety instructions as well.
- Supervise students at all times during hands-on activities.
- Provide sufficient time for students to set up the equipment, perform the investigation, and properly clean up and store the materials after use.
- Never assume that students know or remember safety rules or practices from their previous science classes.

How Can Controversial Topics Be Handled in the Classroom?

Teachers sometimes feel that the discussion of values is inappropriate in the science classroom or that it detracts from the learning of "real" science. The lessons in this module, however, are based upon the conviction that there is much to be gained by involving students in analyzing issues of science, technology, and society. Society expects all citizens to participate in the democratic process, and our educational system must provide opportunities for students to learn to deal with contentious issues with civility, objectivity, and fairness. Likewise, students need to learn that science intersects with life in many ways.

In this module, students are given a variety of opportunities to discuss, interpret, and evaluate basic science and health issues, some in the light of their values and ethics. As students encounter issues about which they feel strongly, some discussions might become controversial. The degree of controversy depends on many factors, such as how similar students are with respect to socioeconomic status, perspectives, value systems, and religious beliefs. In addition, your language and attitude influence the flow of ideas and the quality of exchange among the students.

The following guidelines may help you facilitate discussions that balance factual information with feelings:

- Remain neutral. Neutrality may be the single-most important characteristic of a successful discussion facilitator.
- Encourage students to discover as much information about the issue as possible.
- Acknowledge some issues are not within the scope of the exercise, and offer students opportunities for further exploration.
- Keep the discussion relevant and moving forward by questioning or posing appropriate problems or hypothetical situations. Encourage everyone to contribute, but do not force reluctant students to enter the discussion.
- Emphasize that everyone must be open to hearing and considering diverse views.
- Use unbiased questioning to help students critically examine all views presented.
- Allow for the discussion of all feelings and opinions.

- Avoid seeking consensus on all issues. Discussing multifaceted issues should result in the presentation of divergent views, and students should learn that this is acceptable.
- Acknowledge all contributions in the same even-handed manner. If a student seems to be saying something for its shock value, see whether other students recognize the inappropriate comment and invite them to respond.
- Create a sense of freedom in the classroom. Remind students, however, that freedom implies the responsibility to exercise that freedom in ways that generate positive results for all.
- Insist upon a non-hostile environment in the classroom. Remind students to respond to ideas instead of to the individuals presenting those ideas.
- Respect silence. Reflective discussions are often slow. If a teacher breaks the silence, students may allow the teacher to dominate the discussion.
- At the end of the discussion, ask students to summarize the points made. Respect students regardless of their opinions about any controversial issue.

Using the Student Lessons

The heart of this module is the set of six classroom lessons. These lessons are the vehicles that will carry important concepts related to scientific inquiry to your students. To review the concepts in detail, refer to Table 1 (page 12).

Format of the Lessons

As you review the lessons, you will find that all contain common major features.

At a Glance provides a convenient summary of the lesson.

- ***Overview*** provides a short summary of student activities.
- ***Major Concepts*** states the central ideas the lesson is designed to convey.
- ***Objectives*** lists specific understandings or abilities students should have after completing the lesson.
- ***Teacher Background*** specifies which portions of the background section relate directly to the lesson. This reading material provides the science content that underlies the key concepts covered in the lesson. The information provided is not intended to form the basis of lectures to students. Instead, it enhances your understanding of the content so that you can more accurately facilitate class discussions, answer student questions, and provide additional examples.

In Advance provides instructions for collecting and preparing the materials required to complete the activities in the lesson.

- ***Photocopies*** lists the paper copies and transparencies that need to be made from masters, which are found at the end of each lesson.
- ***Materials*** lists all the materials (other than photocopies) needed for each of the activities in the lesson.
- ***Preparation*** outlines what you need to do to be ready to teach the lesson.

Procedure outlines the steps in each activity of the lesson. It includes implementation hints and answers to discussion questions. Within the Procedure section, annotations provide additional commentary.

Masters required to teach the activities are located at the end of each lesson.

Timeline for the Module

The following timeline outlines the optimal plan for completing the lessons in this module. This plan assumes that you will teach the activities on consecutive days. If your class requires more time for completing the activities or for discussing issues raised in this module, adjust your timeline accordingly.

Table 5.
Suggested Timeline

Timeline	Activity
2 weeks ahead	Obtain supplies for Lessons 2 and 3.
1 week ahead	Copy masters, make transparencies, gather materials. Germinate seeds for Lesson 3.
Day 1 Monday	**Lesson 1** Activity 1: *Essential Nutrients* Activity 2: *Sources of Essential Nutrients*
Days 2 and 3 Tuesday and Wednesday	**Lesson 2** Activity 1: *Properties of Soils*
Day 4 Thursday	**Lesson 3** Activity 1: *From Soil to Roots* Activity 2: *From Roots to the Plant*
Day 5 Friday	**Lesson 4** Activity 1: *Take a Plant to Dinner* Activity 2: *Humanity Against Hunger*
Day 6 Monday	**Lesson 5** Activity 1: *The Big Apple* Activity 2: *Using Land Wisely* Activity 3: *Fertilizers in the Future*
Day 7 Tuesday	**Lesson 6** Activity 1: *Nourishing the Planet in the 21st Century*

Nourishing the Planet in the 21st Century

Teacher Background

1.0 Introduction

We are fortunate to live in a society with abundant food. Most of us take for granted that we will always have enough to eat. If we do have any concerns about food, more than likely they relate to its nutritional value or to reducing the epidemic of obesity. Many of us have never visited a working farm, let alone tried to understand the techniques that farmers use to grow our food. A by-product of the success of modern agriculture is a society where the efforts of the few are adequate to feed the many. This situation allows the vast majority of people to engage in diverse occupations without worrying about the need to grow food to feed their families.

Of course, it has not always been this way. For most of human history, the world's population increased at a steady but slow rate. However, during the last 100 years, the rate of population growth increased to such an extent that more-efficient farming methods weren't just desirable but essential to avoid massive famine. In 1950, the world's population reached 3 billion people. The population then doubled in just 50 years. This rapid population growth was accompanied by the implementation of farming practices such as the increased use of commercial fertilizers to replenish soil nutrient deficiencies. During this so-called Green Revolution, crop yields increased enough to keep pace with the demand for food. In 1950, 790 million hectares of farmland were used to produce 628 million tonnes of grain. By 1992, essentially the same land produced 1.7 billion tonnes of grain.[10] Not only did the Green Revolution help feed our growing population, it also limited the amount of land that was cultivated to raise crops. If populous India had not used the high-yielding crops developed during the Green Revolution, then it would have had to farm additional land roughly about two thirds the size of Saskatchewan to produce the same quantity of grain.

However, the advances of the Green Revolution have almost reached their potential for increasing crop yields. At the same time, the human population shows no inclination to stop growing. It is estimated that by 2050, the world's population will be between 8 and 9 billion people.[29] How will all of these people be fed? Most of the land suitable for farming is already being tilled. We have no choice but to explore other ways of increasing crop yields and sustaining the quality of our soil.

The challenge for the future is complex. We must feed a population that grows by 80 million people each year, using the same amount of farmland. Clearly, the farming practices of the past are not going to be able to sustain us in the future. Our response to this challenge involves making difficult decisions about land use, commercial and organic fertilizer sources, crop protection genetically-modified seed varieties, and

social issues that extend well beyond the scope of this material. As a global society, we will have to decide how agriculture can economically feed our growing populations, while at the same time we must maintain the capacity to protect our environment.

These issues will become increasingly important in the decades to come. As today's young people become adults and enter the workforce, they will be asked to make decisions regarding the use of natural resources such as farmland. Hopefully, they will make rational decisions to benefit society.

The aim of the *Nourishing the Planet in the 21st Century* module is to help prepare students to meet the challenges of the future. The lessons are designed to enhance students' basic understanding of plant biology and the process of scientific inquiry. They help develop critical-thinking skills in the real-world context of sustainably nourishing the planet's growing population. The module focuses on plant nutrients: exploring what they are, why they are important, where they come from, what their impacts are, and how they can be managed.

2.0 Plants and Their Essential Elements

All organisms must take in matter from their environment in order to survive. There are 92 naturally occurring elements on Earth. Only a minority of them is needed by living things. For example, humans require about 21 different elements to be healthy.[22] Almost all of the mass of our bodies comes from just six of those elements (carbon, hydrogen, oxygen, nitrogen, phosphorus, and calcium). These are the elements used to construct the carbohydrates, nucleic acids, proteins, and other molecules that make up our cells and carry out their chemistry. Other elements critical to our health are needed in very small amounts. Often, such elements are cofactors required by enzymes to catalyze specific chemical reactions. Regardless of whether elements are needed in large or small amounts, they must be obtained from the environment. Furthermore, it not enough that essential elements are present in the environment; they must be available in a chemical form that our bodies can use.

Not surprisingly, the situation in plants is similar. They, too, must carry out thousands of different chemical reactions, many of which are similar to those of humans. Scientists have identified 17 elements that are described as essential elements (see Table 6).[2] An element is described as being essential to the plant if the following conditions are met:

- The element must be required by the plant to complete its life cycle.
- The element can not be replaced by another element.
- The element must be required for a specific biological function.[1]
- The element must be required by a substantial number of different plant species.

Three essential elements (carbon, hydrogen, and oxygen) are classified as non-mineral nutrients because they are obtained from the atmosphere and water. Three others (nitrogen, phosphorus, and potassium) are classified as macronutrients because they are needed in relatively large amounts. These six elements have important roles to play as building blocks for a cell's biomolecules, such as proteins, nucleic acids, and carbohydrates. Three additional elements (calcium, sulphur, and magnesium) are called secondary elements, reflecting their supporting biochemical roles in the cell. The rest of the essential elements are called micronutrients because they are needed in small amounts. It is important to note that despite their name, micronutrients are just as essential to plants as are macronutrients.

The large majority of essential elements are absorbed by plants from water in the soil. Almost always the essential elements are taken up as a positively charged cation or a negatively charged anion. Of special interest is the situation regarding nitrogen. Although the atmosphere is about 80 percent nitrogen, plants cannot make use of nitrogen gas (N_2). Instead, plants need to obtain their nitrogen by taking up the cation ammonium (NH_4+) or the anion nitrate (NO_3-) in the soil. These ionic forms of nitrogen are generated by the breakdown of organic material in the soil or through a process called nitrogen fixation that is carried out by soil microbes. Some crop plants (legumes such as peas, beans, peanuts, and soybeans) live in close association with nitrogen-fixing bacteria that live in their roots and convert N_2 gas to a form that plants can use (i.e. ammonium NH_4-). Such crops have a steady source of nitrogen and don't require nitrogen-containing fertilizers.

Table 6.
Essential Plant Nutrients

Element	Symbol	Classification	Chemical Form Taken into the Plant
Hydrogen	H	Nonmineral nutrient	H_2O
Oxygen	O	Nonmineral nutrient	O_2 and CO_2
Carbon	C	Nonmineral nutrient	CO_2
Nitrogen	N	Macronutrient	NH_4^+ and NO_3^-
Phosphorus	P	Macronutrient	$H_2PO_4^-$ and HPO_4^{2-}
Potassium	K	Macronutrient	K^+
Calcium	Ca	Secondary element	Ca^{2+}
Magnesium	Mg	Secondary element	Mg^{2+}
Sulphur	S	Secondary element	SO_4^{2-}
Boron	B	Micronutrient	$B(OH)_3$
Chlorine	Cl	Micronutrient	Cl^-
Copper	Cu	Micronutrient	Cu^{2+}
Iron	Fe	Micronutrient	Fe^{2+} and Fe^{3+}
Manganese	Mn	Micronutrient	Mn^{2+}
Molybdenum	Mo	Micronutrient	MoO_4^{2-}
Nickel	Ni	Micronutrient	Ni^{2+}
Zinc	Zn	Micronutrient	Zn^{2+}

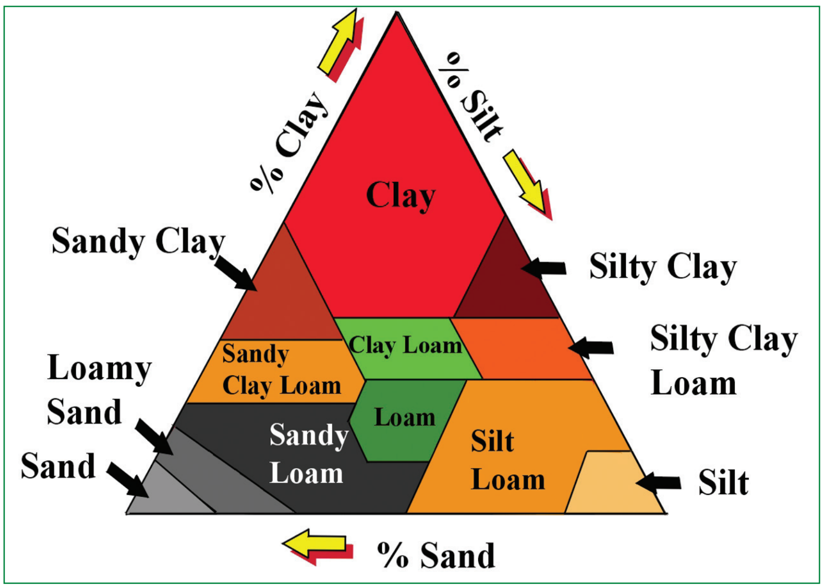
3.0 Properties of Soils

As with agriculture, we generally don't think much about the soil. In fact, "soil" has a negative connotation. We call it dirt and wash it off our clothes and our bodies. In reality, the soil is essential to our survival and that of nearly every organism on Earth. Our planet is mostly made of rock with an iron-nickel core. Plants and animals, including us, occupy a thin veneer on its surface. Our existence is possible because of a thin layer of soil that comes between us and the planet's rocky interior.

Soils are slowly produced by the weathering of rock. Constant exposure to wind and rain cause the rocky crust to slowly break down into smaller particles. It can take centuries to produce fertile topsoil. As rainwater seeps into cracks, temperature extremes cause the water to freeze. The rock expands, contracts, and fractures. These weathering actions are helped along by organisms that live on and in the soil. Soils are composed of inorganic material derived from rock and organic material derived from living and dead organisms. Both are important to support plant growth. Some scientists believe that without life, soils are just dirt.

As inorganic material is broken down by weathering, particles of various sizes are produced. Soil texture refers to the relative proportions of different-sized particles found in the soil. Scientists classify soil particles into three categories. The smallest particles, which measure less than 0.002 millimetres, are called clay.[23] Clay is important in holding nutrients. Clay particles form plate-like structures that act like magnets, holding nutrients until they are displaced by another element, absorbed by a plant root, eaten by a soil microbe, or chemically absorbed into the soil. The next largest particles are called silt. Silt particles range in size from 0.002 millimetres to 0.06 millimetres. Sand refers to the largest particles. Sand grains range in size from 0.06 millimetres to 2 millimetres. Soils vary in their proportions of clay, silt, and sand. Soil scientists classify different soil types using the soil triangle. Each side of the soil triangle represents the amount of a soil component, clay, silt, or sand. The relative amounts of these three particle sizes intersect within the triangle and determine to what type of soil those proportions correspond.

Figure 1.
The soil triangle is used to classify soil types.



The ability of a soil to accept and retain water is largely determined by the relative amounts of clay, silt, and sand present. Porosity refers to spaces in the soil that can hold either air or water. Permeability is defined as the rate at which water can travel through soil. Table 7 lists properties of particle size that relate to soils' interactions with water. Soils with desirable properties for farming are called loams. Loamy soils typically contain about 50 percent air space, which allows root systems to "breathe" (i.e. obtain O_2 for respiration). The solid half of soils is about 90 percent minerals and 10 percent organic material. Usually, loamy soils have names that more accurately reflect their composition, such as clay loam or silt loam.

Table 7
Properties of Soil Particles

Property	Clay	Silt	Sand
Porosity	Mostly small pores	Mostly small pores	Mostly large pores
Permeability	Slow	Slow to moderate	Rapid
Water-holding capacity	Large	Moderate	Limited

Although the organic fraction of most soils is small in volume compared to the mineral fraction, it plays an important role in supporting plant growth. The organic material is composed of living organisms, plant roots, and plant and animal residue. A single gram of healthy topsoil may contain 100 nematodes (small roundworms), 1 million fungi, and 1 billion bacteria.[31] Present in smaller numbers may be earthworms and a wide variety of insects. Organic material contains a significant amount of nutrients and it, together with plant roots, help

- decrease erosion;
- increase water infiltration and storage;
- act as a pH buffer (to maintain an acid-base balance);
- decompose organic material, releasing nutrients;
- recycle carbon, nitrogen, and other nutrients; and
- retain available nutrients such as metal ions.

The soil is a "bank" for nutrients that are taken up by plants, and these nutrients must be replenished for continued plant growth. Before the advent of modern agriculture, farmers relied solely upon tillage to break down existing organic material and release existing soil nutrients. This practice is still used in many less developed countries.

4.0 Plant-Soil Interactions

Plants use their root systems for structural support, stability and nourishment. If you have ever seen a tree toppled by high winds, you have some idea of why trees are so stable. Even so, much of the root system remains in the soil, hidden from view. The primary function of the root system is to absorb water and nutrients from the soil. To do this, the root system is ever changing over the course of the plant's life, capable of growing year-round, provided that conditions for growth are met and there isn't competition from the plant's top system. Roots also may serve as storage organs for starch or sugars. Carrots, beets, radishes, turnips, and potatoes are examples of storage roots.

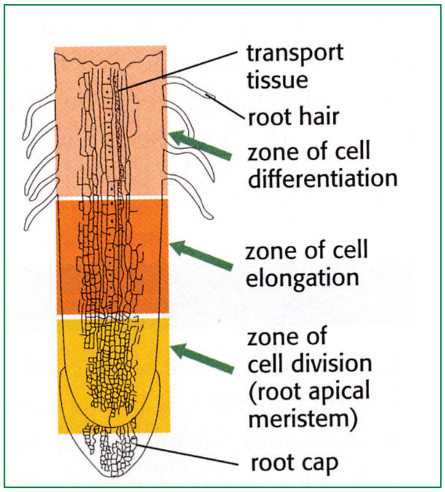
The growth of roots is similar to the growth of shoots. However, there are important differences. In general, the more extensive a root system is, the more water and nutrients it can absorb. If you examine a root using a magnifying glass, you will see a large number of delicate, white root hairs growing out from the surface of the root (see Figure 2). This network of root hairs greatly increases the surface area of the root available to contact and absorb water. A single rye plant 60 centimetres tall is estimated to have a root system with a total length of 480 kilometres. Its surface area is more than 600 square metres—twice that of a tennis court![7]

Figure 2.
A radish seedling showing root hairs

The tip of an actively growing root is called the root cap (see Figure 3). The root cap produces a slimy secretion called mucilage that helps lubricate the root as it pushes its way through the soil. Just behind the root cap is the zone of active cell division, and behind it is a zone of cell elongation. The cells of the elongation zone grow by taking in water and swelling. The root cells contain salt and sugars. Because the root cells contain more solutes than the water in the soil, water flows into the cells by diffusion. This causes the cells to elongate, forcing the root deeper into the soil.

Figure 3.

A longitudinal section of a root tip



Behind the elongation zone is the zone of cell differentiation. The cells in this area give rise to the cells of the vascular system, which transport water up the stem and sugars down from the leaves.

Roots may stop growing during the winter, not because they have become dormant like the buds at the top of the plant, but rather because the temperature is too cool to support growth. In order for roots to grow, they must have adequate moisture and temperature. Many people are under the misconception that roots grow in search of water. This isn't the case. Roots can only grow where the conditions are suitable for growth. This means that roots grow where water is already present.

Water is absorbed by the root hairs and brings along with it any chemicals, including nutrients that are dissolved in it. Most nutrients are present in higher concentration in the root hairs as compared with the soil water. Active transport is used to move the nutrients deeper into the root system until they reach cells of the vascular system. The importance of active transport can be demonstrated by exposing plants to a chemical that interferes with cellular respiration. Without a supply of energy-containing ATP molecules produced through respiration, the rate of nutrient movement slows greatly.

5.0 The Plant Vascular System

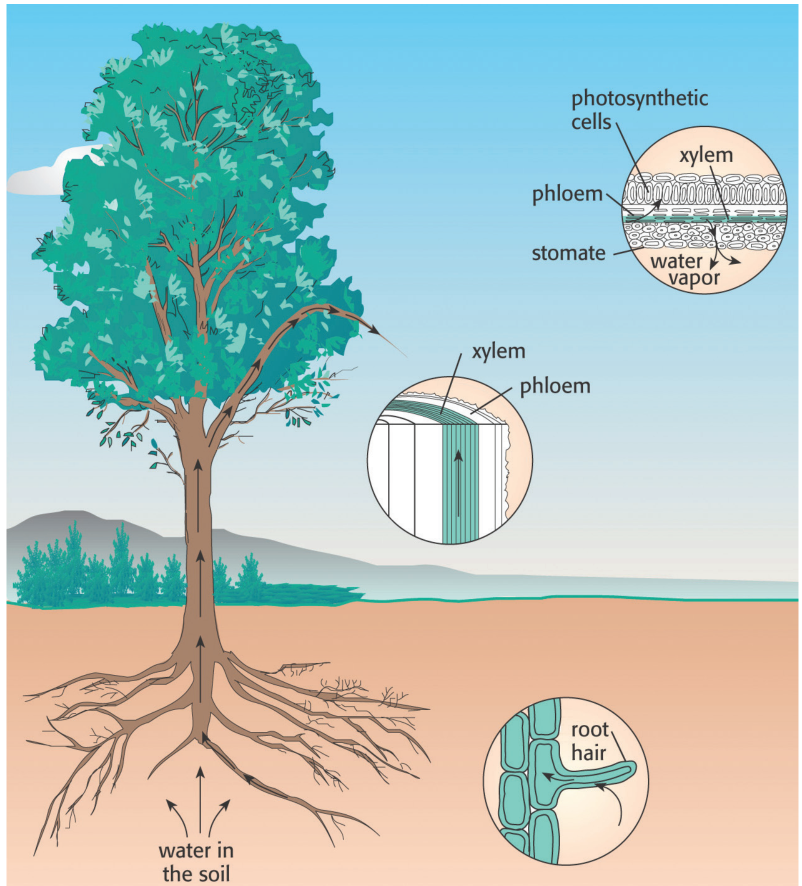
Although plants don't have a circulatory system like humans, they still must transport material from one part of the organism to another. The plant stem contains a vascular system that connects the leaves to the roots. The plant's vascular system is composed of xylem tissue that transports water from the roots to the rest of the plant and phloem tissue that transports sugars produced in the leaves to the nonphotosynthetic parts of the plant (see Figure 4). The xylem is composed of dead cells that form long, empty tubes. Some tubes are wide, and others are narrow. The cell walls within the tubes are either missing or contain a series of holes that permits the passage of water. The cells that gave rise to the xylem lay down thick cell walls that contain a polymer called lignin. Lignin lends strength to the xylem and prevents it from collapsing under pressure.

The capability of xylem tissue is truly amazing. In the case of the tallest trees, water must be transported from the roots up, over 100 metres and against gravity, to the leaves. Water is thought to move through the xylem by a process known as cohesion-tension. According to this view, water can be pulled upward provided that the diameter of the tube is sufficiently small and that the column of water is continuous, that is, without air bubbles. A further requirement is that the tube be made of a material to which water molecules will adhere. Within each xylem tube, the water molecules are attracted to adjacent water molecules, forming an unbroken chain. The plant loses water through evaporation from its leaves by a process called transpiration. As water is lost, a negative pressure or tension is created that pulls water up from the xylem. Transpiration is the process that drives the transport of water from the roots up through the stems to the leaves.

While water is moving up the plant, sugars and amino acids must move from the leaves downward to the nonphotosynthetic parts of the plant. Phloem tissue is composed of tubes made from living cells called sieve cells. Holes at the ends of their cell walls form sieve plates. The cytoplasm of one sieve cell connects with the cytoplasm of adjacent sieve cells through these holes, forming a continuous cell-to-cell sieve tube. As the sieve cells mature, they lose their nuclei and other organelles. Beside each sieve cell is a smaller companion cell that has a nucleus. The companion cells are thought to regulate the activity of the sieve cells.

Experiments have demonstrated that this movement occurs at a rate that is thousands of times faster than could be achieved by diffusion. Sugars are thought to move through the phloem by a process called pressure-flow. According to this view, water and dissolved sugars flow through sieve tubes from areas of higher pressure to ones of lower pressure. Sugars made in the leaves are transported into the phloem by active transport. The high concentration of sugar causes water to flow into the phloem cells, increasing what is called the turgor pressure within the cell. This high turgor pressure forces the sugar-water solution into the adjacent phloem cell, increasing its turgor pressure. This process repeats, moving from cell to cell until the solution reaches a cell where it will be used. Once at its destination, the sugar is removed from the phloem by active transport. Water, too, is removed from the phloem cell, regenerating the lower turgor pressure needed to keep the flow moving.

Figure 4.
Water transport in a tree



6.0 Nutrient Deficiencies of Plants

People and plants are very different types of organisms. For example, people have blood, while plants have sap. People are consumers, while plants are producers. Despite their many differences, both people and plants are made up of cells. In order for cells to be healthy, they must have certain nutrients. If a person is lacking a needed vitamin, mineral, or essential element, then a deficiency is the result. We are familiar with the results of some nutrient deficiencies. For example, if a person lacks iron, he or she becomes anemic or if a person lacks calcium, his or her bones become brittle. As discussed in section *2.0 Plants and Their Essential Elements*, plants require a variety of elements to be present in different amounts in order to support healthy growth. A nutrient deficiency results if a particular nutrient is not available in sufficient quantity to meet the needs of the growing plant. Nutrient toxicity occurs when a nutrient is present in such an excess that it harms the plant. Table 8 lists most of the essential plant nutrients and describes what hap-pens when plants have too little or too much of them.

Table 8.

Symptoms of Plant Deficiencies and Toxicities

Plant Nutrient	Condition	Symptoms
Nitrogen	Deficiency	Light green to yellow leaves; stunted growth; low protein level; poor fruit development
	Toxicity	Dark green leaves; susceptible to drought, disease, and insects
Phosphorus	Deficiency	Purple coloration on leaves; stunted growth and delay in development; increased disease; reduced drought tolerance
	Toxicity	Micronutrient deficiencies, especially zinc or iron
Potassium	Deficiency	Yellowing on edges on older leaves, dead leaves; irregular fruit development; reduced drought tolerance
	Toxicity	Nutrient deficiencies in magnesium and possibly calcium
Calcium	Deficiency	Poor fruit development and appearance; symptoms appear in new leaves and shoots
	Toxicity	Deficiencies in magnesium or potassium (from precipitation in soil)
Magnesium	Deficiency	Yellowing on older leaves; poor fruit development
	Toxicity	Growth reduction possibly due to imbalance with calcium and potassium
Sulphur	Deficiency	Yellowing on younger leaves; otherwise similar to nitrogen deficiency
	Toxicity	Premature dropping of leaves
Iron	Deficiency	Yellow or white areas on young leaves, leading to spots of dead tissue
	Toxicity	Bronzing of leaves with small brown spots
Manganese	Deficiency	Yellowing or mottling on young leaves
	Toxicity	Brown spots on older leaves
Zinc	Deficiency	Yellowing on young leaves; stunted growth; delayed maturity
	Toxicity	Possible iron deficiency
Boron	Deficiency	Deformed and discolored leaves; death of growing points
	Toxicity	Yellowed leaf tips, scorched appearance; premature leaf dropping
Molybdenum	Deficiency	Overall chlorosis, mottled spotting
	Toxicity	Bright orange leaves

Adapted from Bennett, W. (Ed.). (1993). ***Nutrient deficiencies and toxicities in crop plants.*** St. Paul, MN: APS Press.

As discussed above, when a plant is out of nutrient balance, it displays symptoms that are characteristic for that particular nutrient. A farmer concerned for the health of his or her crops must use scientific tools to prevent deficiencies and, if necessary, to examine these symptoms and diagnose problems, much like a physician does when encountering a patient with a dietary deficiency. Soil and plant tissue tests are used to detect nutrient imbalances. Once the problem has been identified, steps are taken to correct the imbalance. Farmers prescribe fertilizers for their crops in a manner similar to doctors prescribing vitamins for their patients.

7.0 Nourishing Crops with Supplemental Plant Nutrients

As discussed above, plants grown in soil depleted of nutrients can display a wide variety of symptoms and greatly limit the quantity and quality of harvested crops. Commercial fertilizer and recycled biosolids such as manure are essentially plant food. They are added to replenish soil nutrients that people indirectly extract from the soil by harvesting plants. In non-agricultural ecosystems, the nutrients removed by plants are returned to the soil after the plants die and decompose. On farms, some of these nutrients are removed in the form of harvested crops, so it is often necessary to replace them. The essential components of most organic or mineral fertilizers are the macronutrients nitrogen, phosphorus, and potassium. . All three of these elements play essential roles in allowing plants to access the free energy of the sun through photosynthesis and must be present in adequate amounts to ensure healthy crop growth.

Table 9.
Importance of Some Essential Macronutrients

Nitrogen
- Component of proteins and nucleic acids.
- Required for chlorophyll production.

Phosphorus
- Component of nucleic acids and some proteins.
- Required for energy transfer.
- Important for seed germination and water use.

Potassium
- Required as a regulator involved in
  - o Efficient use of water.
  - o Transfer of food.
  - o Protection against stresses.

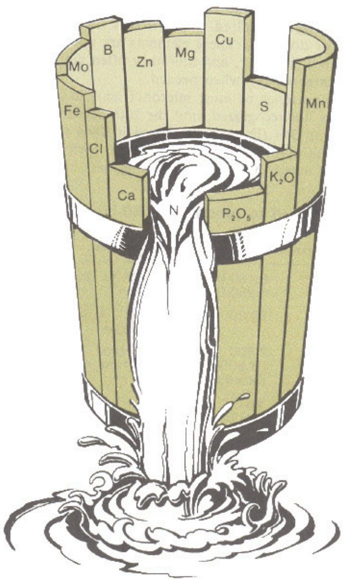
Sulphur
- Component of proteins.
- Required for enzymes associated with
  - o Photosynthesis.
  - o Chlorophyll production.
  - o Nitrogen fixation.

Humans have been raising crops for nearly 10,000 years. Even ancient farmers fertilized their crops. The use of human and animal waste to increase soil fertility was recorded in China over 2,000 years ago. During the "golden age" of Greece from 800 to 200 BC, historians discussed methods for using sewage and classifying manures according to their value for crop production. Although these ancient cultures lacked our understanding of chemistry, they were observant and learned through trial and error how to help their crops grow. Mineral fertilizer in the form of saltpetre or potassium nitrate is mentioned by early Greek and Roman writers and in the Bible. Ancient Greeks also used salt brines to fertilize palm trees.[4]

Justus von Liebig (1803–1873) is known as the founder of the modern fertilizer industry. Using the contributions of other scientists as well as his own discoveries, Liebig formulated the "mineral theory," which held that crops "grow or diminish in exact proportion" to the amount of nutrient applied. Liebig stressed the value of replacing nutrients to maintain soil fertility. He also developed the "law of the minimum," which states that if one essential element is deficient, then plant growth will be lacking even when all other essential elements are abundant. If the deficient element is supplied, then growth will increase up to the point where the supply is no longer the limiting factor.[11]

The concept of the law of the minimum has been modified through the years as scientists have achieved a better understanding of the variables affecting plant growth. Moisture, temperature, insect control, weed control, light, plant population, and genetic capabilities of plant varieties are now part of this rule.

Figure 5.
According to the law of the minimum, plant growth will be harmed if just one essential element is lacking.



The world's first commercial fertilizer was sodium nitrate mined from natural deposits in Chile and imported into the western world starting around 1830. Around the same time, ammonium sulphate, a by-product of the manufacture of coal gas used for illumination, was sold as a commercial fertilizer.[4]

Today, commercial fertilizers are obtained from a variety of natural sources which are then processed in a variety of ways, as described in the sections below. The mining, manufacturing, transport and sale of commercial fertilizers plays an important role in the Canadian and global economies. Commercial fertilizer production in Canada is subject to environmental regulations, as are other manufacturing processes.

7.1 Nitrogen (the Builder)

Nitrogen (N) is a primary building block for all organisms. It is a component of every amino acid and therefore essential to making proteins. As part of the chlorophyll molecule, nitrogen helps keep plants green. Nitrogen, along with magnesium, is the only element in the chlorophyll molecule that the plant obtains from the soil.

Vigorous plant growth is associated with adequate nitrogen nutrition, in part because nitrogen plays a key role in cell division. If cell division is slowed or stopped, so is leaf growth, which affects the surface area of the leaf exposed to the sun. A smaller surface area reduces the plant's ability to produce biomass (yield). In addition to increasing yield, nitrogen also improves crop quality by increasing its protein content. Crop plants generally require more nitrogen to grow at their full potential than non-crop plants.

In 1918, scientists Fritz Haber (1868–1934) and Carl Bosch (1874–1940) were awarded the Nobel Prize for developing nitrogen fertilizer by synthesizing ammonia from nitrogen gas and hydrogen. While this process has been modified several times, today the Haber-Bosch process remains the method by which nitrogen fertilizer is commercially produced. The Haber-Bosch process has increased the amount of plant-available nitrogen produced on land by 60-70 percent compared to the natural processes of biological nitrogen fixation and lightening, and it is estimated that commercial nitrogen fertilizer makes possible 48 percent of the world's crop production.[31] In Canada, ammonia is both used as a fertilizer, primarily in the prairie regions of the western provinces, and is the building-block for all other nitrogen fertilizers (except mined nitrates). Ammonia use decreases in volume from western Canada to eastern Canada (north-east BC, AB, SK, MB, ON, QC). Ammonia is not directly used east of Quebec due to soil conditions, crops grown, field size, and fertilizer handling facilities. Ammonia contains 82 percent nitrogen; another nitrogen source is urea, which is made by combining ammonia with carbon dioxide from the air, and is 46 percent nitrogen.

Organic sources of nitrogen have long been used as fertilizers. Recycling of nutrients in the form of animal manures has been practiced for thousands of years. Between the years 1850 and 1900, other recycled organic sources were human excrement, cottonseed meals, fish scrap, and slaughterhouse wastes. Until 1910, Canadian agriculture obtained the nutrient of nitrogen primarily from sources such as animal manure, peat, seaweed and guano (Chilean nitrate). As use of commercial fertilizers grew in Canada, the proportion of nutrient contributions from organic sources declined, but organic sources are still very important for cropped land, especially near livestock operations, It is estimated that commercial fertilizers supply an estimated 52 percent of all crop nitrogen requirements in agriculture.[16]

A new form of fertilizer was developed in the 1950s called activated sewage sludge. This material is made by passing wastewater through filters and centrifuging it to remove debris, oil, grease, and grit. The wastewater is then oxygenated to help microorganisms break down the biomass. Excess water is removed, and the final product is a thick, fibrous cake that is dried in kilns at high temperature to kill any remaining microorganisms or pathogens.

Figure 6.

The corn leaf on the left is healthy. The leaves to the right have increasing levels of nitrogen deficiency.

7.2 Phosphorus (the Energy Supplier)

Phosphorus (P) is found in every living cell. In plants, it serves as both a structural element and as a catalyst for biochemical reactions. Phosphorus is a component of DNA and ATP (the cell's energy molecule). It also plays vital roles in capturing light during photosynthesis, helping with seed germination, and helping plants use water efficiently. Plants also use phosphorus to help fight external stress and prevent disease.

Animal and human bones contain insoluble calcium phosphate. As early as 2,000 years ago, Chinese farmers treated bones with lime and spread them on their fields. The lime treatment was necessary to convert the calcium phosphate into a more soluble form that plant roots could absorb.

Buffalo bones were also used as fertilizer. In the early 1800s south Saskatchewan was home to a large number of buffalo, and thousands of aboriginals in the area depended on them for food and use of their skins for clothing. The Wascana Creek in Saskatchewan was ideal for capturing buffalo. The Cree piled up the bones because they believed that the living buffaloes would not leave the bones of the dead buffaloes, and that as long as there was a pile of bones, there would be buffalo to hunt. The pile of bones, which the Cree named "Okana ka-asateki," was at times 2 metres high and 13 metres in diameter. When Irish explorer Colonel John Palliser arrived in Canada in 1857, he heard the Cree name, and called the creek Wascana. Prior to this, the settlement was called Pile-o-Bones. The actual pile of bones was sold by settlers for fertilizer production for a rumoured $15,000. [16]

In the 1800s, fertilizer manufacturers wanted to produce phosphorus fertilizers that were more effective and plentiful than bones. They turned to natural deposits of phosphate rock in the fossilized remains of ancient marine life found in rock deposits around the world. The phosphate in these deposits exists in various forms of a very stable compound called apatite. To make phosphate fertilizer, the phosphate rock is treated with acid or heat to render the phosphorus more soluble and thus more available for plant use. Superphosphate production began in the United States in South Carolina in 1849.

Figure 7.
Corn plants deficient in phosphorus have some leaves with purplish discoloration.

7.3 Potassium (the Regulator)

Potassium (K) is essential to the workings of every living cell. Although potassium is not a part of any important plant structure, it plays critical roles in several physiological processes. Potassium activates enzymes that catalyze chemical reactions involved with growth. It plays an important role in water balance by regulating the opening and closing of stomates (the pores in leaves through which gases are exchanged). Potassium also helps regulate the rate of photosynthesis through its role in the production of ATP. Other aspects of plant health influenced by potassium include the growth of strong stalks, protection from extreme temperatures, and the ability to fight stress and pests such as weeds and insects.

Potassium used in the manufacture of fertilizers comes from sedimentary salt beds left behind following the evaporation of ancient seas and lakes. Nearly all potassium fertilizer is in the form of potassium chloride, with lesser deposits of potassium sulfate. The potassium fertilizer industry started in Western Europe, where there are significant deposits of such ores. Canada has some of the world's largest reserves of potassium deposits with most of these in Saskatchewan and a smaller deposit in New Brunswick. Canada is the world's foremost supplier of potassium fertilizers.

Figure 8.
Leaf from a potassium-deficient corn plant. The dark spots are areas where cells have been killed.

7.4 Sulphur (the Synthesizer)

Sulphur (S) is one of the most abundant elements in the soil and is one of the first elements scientists described. Like nitrogen, it is an essential component in the life of a cell. Sulphur is a component of the amino acids methionine and cysteine, which are used in the synthesis of proteins in all living things. Sulphur also is needed by enzymes associated with photosynthesis and chlorophyll synthesis. Sulphur is extracted from natural gas and crude oil, from the smelting of certain metal ores, and from gases produced by burning coal.

7.5 Micronutrients

Among the micronutrients, the following four types of deficiencies are commonly addressed through the use of fertilizers:

- **Boron (B)** is an essential nutrient in the growth and development of new cells. In plants, boron helps regulate flowering, pollination, seed development, and sugar transport.
- **Copper (Cu**) is a critical regulator of several plant enzyme systems and is necessary for protein synthesis and nitrogen metabolism.
- **Manganese (Mn)** is a part of several plant enzyme systems and plays a role in photosynthesis by regulating chlorophyll synthesis.
- **Zinc (Zn)** is an essential enzyme regulator involved with the synthesis of protein, starch, and growth hormones.

7.6 *Organic and Commercial Fertilizers*

There has been an increase in the sale of certified organic products through traditional mainstream grocery stores. In 2006, the Organic Agriculture Centre of Canada (OACC) reported that total sales of certified organic food had grown 28% overall from 2005 to 2006. The number of certified organic farms in Canada has grown nearly 60% since 2001 with Saskatchewan, followed by Quebec, continuing to be the province with the most organic farms. In spite of this growth, less than 1% of the $46.5 billion spent by Canadians in national grocery sales during 2006 was attributed to certified organic sales.[15]

Farmers who fertilize their crops have the choice of using either organic or commercial fertilizers, or a combination of the two types. As the name suggests, organic fertilizers come from once-living material such as plants or animal manure. Commercial fertilizers consist of natural ingredients that have been subjected to processing to make a fertilizer. Commercial fertilizers come from either natural mineral deposits or, in the case of nitrogen, from Earth's atmosphere.

From a plant's point of view, there is no difference between a nitrogen atom that comes from fertilizer, animal manure, a compost pile, or the atmosphere. If they are in the same form (e.g. ammonium, nitrate or urea) they are the same as far as the plants are concerned. However, there are differences in the rate at which the nitrogen from each of these sources is made available to plants and the ratio of nitrogen to other elements such as phosphorus.

A major distinction between organic fertilizers and commercial ones is the quantities of nutrients they contain and the farmers' knowledge about and ability to measure those quantities. Unlike commercial fertilizers, organic nutrient sources typically do not come with a guarantee of nutrient content. Organic material may supply high levels of one nutrient but low levels of another, creating an imbalance for crop plants. In contrast, commercial fertilizers contain known and often higher quantities of nutrients, which make it convenient for farmers to apply them at rates that ensure that growing plants' needs are met and nutrient losses to the environment are minimized.

An advantage of plant-based organic fertilizers (e.g. compost) is that the nutrients are released slowly, so they are less likely to be supplied faster than plants can use them. For this reason they are often considered less damaging to the environment than mineral fertilizers. However, manure-based organic sources are typically more volatile—or subject to movement—in the environment than commercial fertilizers. If any nutrient—commercial or organic—is applied at a rate higher than plants can use it, the excess may run off the fields or disperse into the air and contribute to nutrient pollution (see section *8.1 Nutrient Pollution*). Most organic fertilizers used on farms are manure based.

7.7 *Meeting Crop's Nutrient Needs*

Commercial fertilizers can be applied as liquids or solids or, as in the case of ammonia, as a pressurized gas that is injected into the soil. Commercial fertilizers are sold in a wide variety of mixtures. They are labelled with their NPK content – the percentage by weight of the three macronutrients—–nitrogen, phosphorus, and potassium. For example, a label with an NPK content of 24-6-6 means that the fertilizer contains 24 percent nitrogen, 6 percent phosphorus (P_2O_5), and 6 percent potassium (K_2O). Some fertilizers also contain secondary or micronutrients, which are nutrients needed in smaller amounts for plant health and growth. Fertilizer labels also indicate the amounts of micronutrients as well as any inert ingredients

Figure 9.

This is a label found on a bag of commercial fertilizer. It indicates the proportions of nitrogen, phosphorus, and potassium.

such as sand that are included to provide bulk and make the fertilizer easier to apply. Organic fertilizers prepared for sale to either home or agricultural markets must also carry a label guarantee for their nutrient content. A typical organic label might carry a guarantee of 2-6-4, for example.

Farmers use scientific methods to determine the appropriate nutrient balance for their crops. Because every farm field is different, farmers need to have the flexibility to select the best-management practices (BMPs) that are suited to their growing conditions. Factors that may influence BMP selection include availability of organic sources, soil, climate, topography, and crop nutrient requirements. Often, farmers work with an agronomist or certified crop advisor, a trained nutrient management professional, to assess growing and environmental conditions and develop a nutrient management plan.

The soil composition of farm fields varies greatly—often even on the same farm. Ensuring that crops get the precise amount of nutrients needed while minimizing nutrient losses to the environment involves consideration of a number of variables including the existing nutrient content of the soil and the crop nutrient needs. Soils can contain rich reserves of nutrients. Before fertilizing, farmers must measure the existing amounts of nitrogen, phosphorus, and potassium already in the soil. Then they can select a combination of organic and commercial fertilizers that meet the needs of their crops. Generally, fertilizers are custom-blended to meet the farmer's needs. After the right source or product has been selected, the nutrient management plan must also take into account the criteria described in Table 10.

Table 10.

Use of Fertilizers in Nutrient Management Plans

Criterion	Description
Right rate	Apply nutrients at a rate that the plant can use. If the rate is too low, then optimal yields will not result. If the rate is too high, then nutrients are wasted and can leak into the environment.
Right time	Choose the best time to apply nutrients. This means that the source of nutrients should be applied when the crops need the nutrients. For example, with regard to nitrogen, the material should be applied as close to plant uptake as possible
Right place	Farmers must ensure that nutrients are applied where plant roots can most easily access them. Careful application limits nutrient losses. Avoid environmentally sensitive areas such as those close to surface waters so nutrients will not run off or leach into surface and groundwater.
Right source/ product	Farmers must ensure that the type of organic or commercial fertilizer used matches the crop's needs.

7.8 *Organic or Commercial: Which Is Better?*

A quick answer to the question of which nutrient source is better is that neither organic nor commercial nutrient sources are better for plants. Both have their places and should be used where appropriate. Each has its advantages and disadvantages.

Farmers need to examine the relative merits and decide when and where each type of fertilizer should be used. Because most organic fertilizers used on farms are from livestock, we focus here on manure-based organic fertilizers.

Manure-based organic materials encourage the use of local recycled bio-solid materials. Manure and plant based fertilizers are economical to produce and use, and they provide significant nutrients. They are often used in combination with mineral fertilizers. Organic materials contain varying amounts of plant nutrients and provide organic carbon, which is part of any productive agricultural soil. They improve the biological, chemical, and physical properties of soils.

There are, however, some concerns associated with certain forms of manure-based organic fertilizer. First, when animal manures are produced in confined areas, excessive amounts of nutrients can accumulate in crop fields if the manure is over-applied near the site where it was produced. This can pose a threat of nitrate leaching to groundwater and phosphorus moving into surface waters through runoff and erosion. Second, the relatively fixed nutrient ratios of organic fertilizers can result in too much phosphorus being present in heavily manured soils, because crops usually require much less phosphorus than nitrogen. In addition, significant amounts of ammonia gas (NH_3) can also be lost to the atmosphere.

Figure 10.
Organic farming recycles nutrients by using compost (a) and manure (b).

Compared to manure-based organic fertilizers, plant-based organic fertilizers are usually low in nutrient content. They contain some soluble nutrients, but most are released slowly as microbes in the soil break down the organic material into water-soluble forms that the plant roots can absorb. This feature may be an advantage when fertilizer is applied infrequently because it is less likely to overwhelm the system with soluble nutrients.

Commercial fertilizers contain precise, guaranteed levels of nutrients, in forms that are readily available for plant uptake and use. It is possible to time their application to meet crop requirements, assuring efficient nutrient use and minimizing impacts on the environment. Because of their high nutrient content, commercial fertilizers are easy and economical to ship great distances from their point of production.

However, the high nutrient content of commercial fertilizers also means that the potential for overuse is greater. Farmers need to apply commercial fertilizers as specified by a nutrient management plan that is designed for the specific conditions of their fields. Nutrient management plans use data from soil and plant tissue testing to help farmers use the proper amounts of nutrients at the optimal times. Nutrient management plans accounting for all organic and commercial sources also keep farmers from wasting money by using too much plant nutrients and from contributing excess nutrients to the air, groundwater and local waterways. For example, even though cultivation can increase susceptibility of soil to erosion by wind or water, most adequately fertilized crops produce sufficient plant growth so that the crop residues remaining on the soil surface after harvest can be managed using reduced tillage and adequately control soil erosion.

8.0 Plant Nutrients and the Environment

Nutrient pollution comes from many sources: from natural ecosystem functions, from a wide spectrum of human activity and from agriculture.

Nutrients are a natural part of the environment and enter the biosphere from weathering and erosion processes. Pollution sources from humans include agriculture, sewage and wastewater treatment plants, coal-burning power plants, and automobile exhaust. The relative importance of these nutrient pollutants varies greatly between urban and rural areas. Controlling nutrient pollution means identifying its various sources and implementing policies that limit loss of excess nutrients to the environment.

No one disputes the fact that proper application of organic and commercial fertilizers increases the yield of crop plants. The concern over their use is that plants may be exposed to larger quantities of nutrients than they can absorb, especially when applied improperly. In such cases, the excess nutrients run off the farmers' fields with the rain and enter rivers, streams, lakes, and oceans, where they may cause harm to the environment. While nutrients are essential to aquatic life, excess nutrients in aquatic environments promote the growth of algae and similar organisms, leading to a general degradation of water quality. They can also enter groundwater and the atmosphere where they can contribute to human health problems and global warming.

8.1 Nutrient Pollution

As discussed earlier, organisms require essential nutrients to survive, but they must be present in the proper amounts. Either too little or too much can adversely affect health. A similar situation exists with regard to the environment. One of the largest water quality challenges facing not only Manitoba, but also other jurisdictions in Canada, United States, Europe, and elsewhere is the gradual increase in nitrogen and phosphorus to water systems.

Excessive levels of phosphorus and nitrogen encourages production of algae and aquatic plants. Extensive algae blooms can cause changes to aquatic life habitat, reduce essential levels of oxygen, clog commercial fishing nets, interfere with drinking water treatment facilities, and cause taste and odour problems in drinking water.[18] Nutrient pollution, especially from nitrogen, can lead to explosive growth of aquatic organisms through a process called eutrophication. The resulting blooms of organisms such as phytoplankton and algae reduce the amount of sunlight available to aquatic vegetation. Their metabolism depletes the bottom waters of oxygen, which can suffocate organisms that cannot move away from oxygen-depleted areas. Scientists have shown that the area of oxygen-depleted bottom water is increasing in estuaries and coastal zones worldwide. Excess nitrate in water supplies can cause human health concerns at high concentrations. The most severe acute health effect is methemoglobinemia, often called 'blue baby' syndrome. Recent evidence suggests that there is not a simple association between nitrate and blue baby syndrome, rather that nitrate is one of several interrelated factors that lead to methemoglobinemia.[13] Public drinking water systems should contain nitrates at a level safe for consumption as nitrates can be removed by water filtration.

Nitrogen pollution from cultivated soils, industry and other sources contributes to global warming because a portion is released into the atmosphere as nitrous oxide (N_2O), a powerful greenhouse gas.

Point and Non-Point Sources of Nutrient Pollution

Excess nutrients enter the environment through both natural and human-induced mechanisms. Sources of nutrient pollution are classified as being either point sources or nonpoint sources.

Point sources typically are factories, power plants, and wastewater treatment plants.

Nonpoint sources are general sources, such as farms, cities, and automobiles. A major nonpoint source of nutrient pollution is urban development. For example, clearing of land for housing and industry creates sealed surfaces that do not absorb water and increase nutrient-laden runoff. A related nonpoint source of nutrient pollution is the septic systems that have proliferated as the suburbs extend beyond the reach of urban sewer systems. Another nonpoint source is automobile exhaust. Nitrogen is released first into the atmosphere, but returns to the surface with the rain. Although definitive information is hard to come by, it has been estimated that up to 40 percent of the nitrogen entering aquatic environments in some areas can come from nitrogen in the air.[11] Agriculture is also a nonpoint source for nutrient pollution. Use of organic and commercial fertilizers can send nutrients into the environment, particularly when they are applied in excess of the plant's needs and can quickly move into waterways. Increasingly, farmers are adopting nutrient management and precision agriculture measures that limit the amount of this pollution.

Point sources of nutrient pollution can be tied to specific locations. Most such sources come from wastewater treatment facilities and industrial plants. In urban areas, wastewater treatment facilities can be contributors to nutrient pollution. For example, it is estimated that the City of Winnipeg contributed 4% of the nitrogen and 6% of the phosphorus entering Lake Winnipeg in Manitoba. During the past 40 years, antipollution laws have been enacted to reduce the amounts of toxic substances released into our waters. Under the Canadian Constitution, provinces and territories hold jurisdiction in establishing water-quality standards.[18]

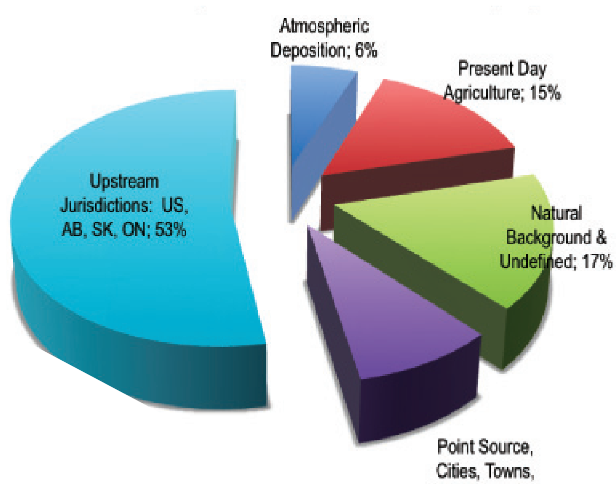


Figure 11.
% Total Phosphorus to Lake Winnipeg Estimated annual phosphorus loading to Lake Winnipeg from Manitoba sources (1994-2001) (Adapted from lake Winnipeg Stewardship Board, 2006)

Provincial governments across the country work to ensure communities are able to protect their municipal drinking water supplies. Municipalities, conservation authorities, property owners, farmers, industry, community groups and the public work together to meet common goals.[28]

8.2 *Managing Lawn Fertilizers*

Concerns have been raised about phosphorus contribution to blue-green algae in Quebec and Manitoba lakes. Blue-green algae, also known as cyanobacteria, develops when more phosphorus than nitrogen is in a lake. Phosphorus is essential to plant growth and farmers depend on phosphorus fertilizer for economically sustainable crop production. Like all fertilizers, phosphorus needs to be carefully managed. Homeowners use science-based best management practices to get the most value from lawn fertilizers and minimize losses to the environment.[9] In Ontario, the township of Georgian Bay recently passed a bylaw banning the application of phosphorus fertilizer.[24] The merit of such legislation is still under debate. However, manufacturers are responding by offering lawn fertilizer with lower amounts of phosphate,

Figure 12.
Fertilizing lawns frequently at lower doses can help reduce nutrient losses.

and the Canadian Food Inspection Agency has introduced a low-P standard for lawn fertilizers. Will these approaches be effective in improving water quality in our rivers, lakes, and reservoirs? The principles of nutrient management that have been developed for agricultural fertilizers also apply to lawn fertilizers. With soil testing and wise application, such as more frequent applications at lower doses, nutrient losses can be reduced.

8.3 *Land Use*

Perhaps surprisingly, commercial fertilizers can have a positive impact on the environment with regard to land use.

A discussion of land use priorities is important. Starting in the 1960s, farmers were able to increase food production about 400 percent. The Green Revolution was made possible largely by three innovations: better crop varieties, use of commercial fertilizers, and better water management practices. The economist Indur Goklany calculated that if we needed to feed today's population of over 6 billion people using the organic methods in use before the 1960s, it would require devoting 82 percent of Earth's land to farming.[11]

Land is a finite resource, and human societies use it for a variety of purposes. We need land for residential living, for industries, for recreation, for wildlife habitats, and of course, for growing food and fibre. Land cultivation worldwide has remained about the same for the past 50 years. Although subsistence farmers in developing countries have brought some additional land into production, land has also been lost to expanding cities in the developed countries.

If, as predicted, the world's population is expected to top 8 billion by 2040, food production will need to keep pace. Without more available agricultural land, we will need to turn to other alternatives – like increasing agricultural productivity – to feed our population.

9.0 Technology and Nutrient Management

Clearly, if we are going to produce adequate food for our growing population, then crop yields will need to further increase. Strategies will have to be developed to meet the challenges of the future. Some farmers are using technology in a variety of ways to increase crop yields. The utilization of these new technologies is growing. The rest of this section describes some of these technologies.

Geographic information systems (GIS) allow farmers to use map-based information about natural resources, soils, water supplies, variability in crop conditions throughout the year, and crop yields to ensure that the amount of nutrients being used matches crop needs. Even information about the amount of crop residue (which still contains nutrients) left at the end of the year and the amounts of nutrients removed by the crop can be "mapped" and stored in a GIS database. Once this information is gathered into one database, it can be integrated with other GIS databases such as rainfall records (taken from Doppler radar).

The global positioning system (GPS) is critical to the development of GIS databases and is used to identify the locations of equipment and people in the field. GPS is also useful in assessing general crop conditions and for scouting fields for problems such as nutrient deficiencies. GPS can help farmers return to the same field sites when problems are being addressed.

Autoguidance is a feature of mechanized agriculture. It ties together GPS, GIS, and robotics technologies, allowing a driver to sit and watch as the machine does the work. This technology is being used in various types of farm equipment such as tractors, combines, sprayers, and fertilizer applicators. For example, by using autoguidance systems, farmers can ensure that applications of fertilizers do not overlap. The best of these systems can apply fertilizer to an accuracy of less than 1.5 centimetres.

Remote sensing uses satellite images of fields to help farmers know what is happening to their crops. The satellite images can be analyzed to detect variability in the reflection of visible, infrared, and other wavelengths of light. Some images show thermal (heat) radiation from the ground below, which helps estimate soil moisture conditions. These images and data, linked with the GIS data mentioned earlier, offer a means of detecting problems developing in the field and comparing successive images over time. The rate of change can be determined to illustrate how a problem is spreading.

Figure 13.

Farmers can use autoguidance systems to accurately apply fertilizers. Such systems tie together GPS, GIS, and robotics technologies.

Enhanced efficiency fertilizers help reduce nutrient losses and improve nutrient-use efficiency by crops while improving crop yields. These products provide nutrients at levels that more closely match crop demand leaving fewer nutrients exposed to the environment. Slow- and controlled-release fertilizers are designed to deliver extended, consistent supplies of nutrients to the crop. Stabilized nitrogen fertilizers incorporate nitrification inhibitors and nitrogen stabilizers, which extend the time that nitrogen remains in a form available to plants and reduce losses to the environment.

Gene modification technology is another strategy with potential implications for the future. One of the main factors that limit crop growth is the efficiency of nitrogen uptake and usage by the plant. If crop plants can be made to more efficiently use nitrogen, lower rates of fertilizer can be applied and with improved crop use there is less potential that will run off into the environment.

The ultimate goal of this research is to give non-legume plants the ability to obtain their own nitrogen from the atmosphere (i.e. to 'fix' nitrogen from the atmosphere) and not relying as heavily on added fertilizers. However, giving a corn plant the ability to fix nitrogen would involve adding a large number of genes, not only from nitrogen-fixing bacteria, but also from an appropriate host plant. The prospect of achieving this anytime soon is remote. Scientists have succeeded in helping plants better use nitrogen by increasing the expression of a single gene. For example, plants that highly express the enzyme glutamate dehydrogenase have been shown to grow larger than those that were not modified to do so. Genetic scientists are not limiting their efforts to nitrogen fixation and are also working to engineer a wide variety of crop plants to grow faster, tolerate unfavourable environments, resist pests, and have increased nutritional value.

10.0 Conclusion

This module helps students better understand the challenge confronting their generation as they seek to nourish the planet's people in the 21st century. Such an ambitious task cannot be fully addressed in the short time used to teach this material.

We have therefore focused our attention on some core scientific concepts that underlie the growth of healthy crop plants and on land use and some downstream issues of pollution that have geographic, social, economic, ecological, legal, political, and ethical implications.

The classroom lessons are designed to introduce students to the notion of essential elements and relate them to the health of plants. Students will see that even though plants seem to be very different from us, their cells work in much the same way as ours do. Just as we need to obtain nutrients from a balanced diet, plants need to obtain a balance of nutrients from the air, water, and soil.

Students will learn to appreciate the soil as a precious natural resource that must be protected. They are instructed to regard the soil as a bank of nutrients that plants use to grow. Nutrients in the soil become dissolved in soil water and are taken up by the plant root system and distributed to the rest of the plant through the xylem tissue. Nutrients enter the roots through the passive process of diffusion and the energy-requiring process of active transport. The exploration of soils reveals that they differ in their composition and nutrient content. Physical properties of soils, such as the amount of air space and particle size, determine how much water a soil can hold and how easily the water moves through it.

The soil "nutrient bank" can only hold a limited amount of nutrients. In non-agricultural ecosystems, plants withdraw these nutrients then return them when they die and decompose. In agricultural ecosystems, some of the nutrients a crop extracts are harvested and taken offsite, which can eventually deplete the soil nutrient bank. As with people, when plants get too little (or too much) of a nutrient, their health suffers. Each type of nutrient deficiency has specific symptoms that scientists and farmers use to diagnose the problem. Fertilizer is 'food' for plants. When a nutrient deficiency is diagnosed, supplemental nutrient additions can be used to restore nutrient balance to the soil.

Students will discover that only a portion of Earth's surface is used to grow the food we eat. They use estimates of population growth and land use to calculate how much additional land will have to be farmed to feed Earth's increasing population. The students will come to realize that growing enough food for everyone involves making some difficult decisions. They are challenged to put themselves in the position of a farmer and to consider the advantages and disadvantages of using organic or commercial fertilizers. At the same time, they must strive to reduce negative impacts on the environment by minimizing contributions to nutrient and other forms of pollution.

As mentioned previously, *Nourishing the Planet in the 21st Century* is not intended to provide a comprehensive look at all the issues associated with food production and population growth. Hopefully, you will find that the module serves as an engaging introduction to some of the important science concepts and societal issues associated with feeding our increasing population. The classroom lessons make explicit connections to relevant Ontario Science curricula and can serve as the basis for a more detailed examination of agriculture and nutrition. You also may find that the module can set the stage for exploring other topics such as global warming and gene modification technology. In short, we hope that you find this module to be a valuable addition to your classroom.

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Glossary

active transport: the movement of substance across a biological membrane against its concentration gradient; from a less-concentrated area to a more-concentrated area. Active transport requires the input of energy and uses specific transport proteins.

ATP: adenosine triphosphate; a compound that has three phosphate groups and is used by cells to store energy.

commercial or mineral fertilizer: commercially prepared mixtures of plant nutrients from mineral or atmospheric source. Nitrogen, phosphorus, and potassium are the most commonly produced and used. Fertilizers are applied to the soil to restore fertility and increase crop yields. Another name for these types of materials is inorganic fertilizers.

concentration gradient: a difference in the concentration of certain molecules over a distance.

cover crop: crops such as rye, alfalfa, or clover can be planted immediately after a crop harvest to hold the soil in place, preventing erosion and nutrient loss. They also represent an important type of fertilizer because they provide nutrient value when they are eventually plowed into the soil. These plant-based fertilizers are used on a small scale in comparison to animal manure-based fertilizers.

crop: food crops, lawns, garden, and ornamental plants such as flowers.

diffusion: the movement of a substance down its concentration gradient from a more-concentrated area to a less-concentrated area.

genetically modified food: a food product containing some quantity of a genetically modified organism (GMO) as an ingredient. A GMO is any organism that has had a gene from another species added to it using recombinant-DNA technology.

Green Revolution: a term used to describe the transformation of agriculture in some developing nations between the 1940s and 1960s, developed by Nobel-winning scientist Dr. Norman Borlaug. During the Green Revolution, already existing technologies such as pesticides, irrigation, and use of inorganic fertilizers spread to developing countries resulting in increased crop yields.

infiltration: the process by which water penetrates into soil from the ground surface.

inorganic fertilizer: (see commercial or mineral fertilizer described above)

lignin: a non-carbohydrate polymer that binds cellulose fibres together. It adds strength and stiffness to plant cell walls.

loam: a rich soil consisting of a mixture of sand and clay and decaying organic materials.

macronutrient: a nutrient that must be present in a relatively large amount to ensure the health of the organism. Macronutrients are building blocks used to make essential biomolecules.

micronutrient: a nutrient required in small quantities to ensure the health of the organism. Micronutrients are often used as cofactors for enzymatic reactions.

microorganism: an organism too small to be seen with the unaided human eye. Bacteria are an important type of microorganism.

nitrogen fixation: a biological or chemical process by which elemental nitrogen, from the air, is converted to organic or available nitrogen.

nonpoint source: nutrient pollution that results from runoff and enters surface, ground water, and the oceans from widespread and distant activities. It comes from a number of different sources, such as agriculture, urban development and automobiles. A non-point source is therefore much harder to trace and quantify than a point-source of nutrient pollution.

nutrient: any of 17 essential mineral and nonmineral elements necessary for plant growth.

nutrient deficiency: a condition where the amount of a nutrient essential to the health of an organism is lacking or present in an insufficient amount.

nutrient pollution: the presence of excessive amounts of nutrients such as nitrogen and phosphorus in waterways. These nutrients stimulate the growth of algae, thus robbing the waters of oxygen and suffocating some aquatic organisms. Nutrient pollution comes from both natural and human-induced sources.

nutrient toxicity: the presence of an excessive amount of a specific nutrient, which is harmful to the organisms.

organic fertilizer: a fertilizer that undergoes little or no processing and is derived from plant or animal materials; also unprocessed mineral sources are sometimes referred to as an organic source.

percolation: the process by which water moves downward through openings in the soil.

permeability: the ability of soil to allow the passage of water.

phloem: a portion of the vascular system in plants, consisting of living cells arranged into tubes that transport sugar and other organic nutrients throughout the plant.

point source: nutrient pollution that comes from a specific source that can be identified such as a factory or a wastewater treatment plant.

porosity: the percentage of soil volume that is not occupied by solids.

transpiration: the loss of water to the atmosphere by a plant through the stomates in its leaves.

xylem: conducting tissue that transports water and dissolved nutrients in vascular plants.