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TEACHING TOOLS IN PLANT BIOLOGY™: LECTURE NOTES

Why Study Plants?

Plants and humans share a common ancestor that lived ~3 billion years ago. People are more like plants than they are like bacteria, but less like plants than they are like fungi. Plants and humans share a common DNA language and a mostly similar cell structure. After diverging from the human and fungal lineages, plants acquired the ability to carry out photosynthesis through incorporating a single-celled photosynthetic bacterium into their cells. This ability to convert the energy from sunlight into chemical energy has allowed plants to occupy a niche completely different from, but highly compatible to, ours; as a by-product of photosynthesis, plants produce the oxygen that we and all other animals need to live. They are also the primary producers of the terrestrial ecosystem; all of the food that animals eat comes directly or indirectly from plants. Furthermore, a complex set of biochemical pathways has evolved in plants, which produce a wide variety of interesting and novel chemical compounds. Many of these compounds function to deter pathogens or herbivores, and some are medicinally useful to us.

THE GLOBAL DEMAND FOR FOOD AND NUTRIENTS IS INCREASING

Plants enrich our lives in many ways, but their role as our source of food is particularly crucial right now. The global population continues to increase. If the global population had stabilized 50 years ago at 3 billion people, the agricultural practices we developed during the first part of the 20th century would be sufficient to feed us all. Instead, the population has more than doubled in the past 50 years, and we simply can't continue to produce enough food without a rapid and sustained change in how we grow plants. Current projections suggest that, to avert large-scale starvation, food production must increase 70% by 2050, when it is thought that the word population may stabilize at roughly 9 billion. It is important to note that alleviating hunger through increased food production, along with attendant improvements in standards of living and education, typically leads to declines in further population growth (i.e., growing more food will not simply lead to greater and greater population growth). Using more land to grow this additional food is not an option; instead, we must grow more food on the land we currently cultivate, and we must increase the yields (mass of product per unit area) of the plants we grow.

There are many kinds of plants, and they live and reproduce successfully in many varied environments. However, we developed a system of agriculture that depends on a small number of plant varieties. Most of the calories humans consume come from grains, primarily rice, wheat, and maize, as well as some legumes. We grow our crops in areas that are often quite different from the ones they evolved in, and we selectively bred them to the extent that frequently they no longer resemble their wild ancestors. A cultivated field of any of our major crops is extremely productive relative to a similarly sized, natural, uncultivated area, both because the plants have been selected for a high biomass and seed production and because, to ensure maximum production, we supply them with additional water and fertilizer (mostly nitrogen, phosphorus, and potassium, but also micronutrients such as magnesium and iron). Agricultural innovations and plant breeding have ensured that crop yields have continually increased to feed our ever-growing population, but meeting the challenges of the future population increase will require even greater increases in agricultural yields. Some plant scientists study plants to augment their productivity by improving plant stress tolerance, growth habit and resource allocation, nutrient use, and pathogen resistance.

Stress Tolerance

Plants can't move away from an unpleasant environment. In the summer growing months, plants can experience a temperature change of nearly 40°C in just a few hours. As we do, plants use evaporation for cooling (called transpiration) and require more water in hotter conditions. Plants are frequently stressed by a combination of heat and not enough water; this stress slows their growth and so lowers their yield, but it can also kill them. Increased irrigation isn't always an option, and globally crop yields are severely decreased by drought stress. Disturbingly, the changing climate is causing lower than usual crop yields because of unusually high temperatures and drought conditions in many areas.

Plant scientists are investigating how plants cope with various kinds of environmental stress by identifying the adaptations they have evolved and varieties as well as genes that are correlated with greater tolerances to stress. Some of these genes reduce the rate of water loss by transpiration, while others affect root growth pattern and water uptake. Plant yields are also affected by unseasonable cold or flooding. Recently, a variety of rice called *Sub1* has been developed that can survive prolonged submergence. In areas that are prone to flooding, this variety is allowing farmers to raise rice without the fear of losing it to an unforeseen flood. (There are several links with more information about this research in Additional Resources.)

Nutrient Use

Crop plants withdraw nutrients from the soil and metabolize them into proteins and other compounds. Each harvest depletes nutrients from the soil, which must be replenished regularly. An

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early agricultural insight was the beneficial effect of legumes, whose associated nitrogen-fixing bacteria replenish soils; the basis of crop rotation is to alternate nitrogen-depleting grains with legumes. For many reasons, crop rotations often aren't practical; instead, crops are fertilized with a mixture of nutrients that includes primarily nitrogen, phosphorus, and potassium, as well as micronutrients like copper, zinc, and iron. Potassium and phosphate are limited resources that are being rapidly depleted. Nitrogen is readily available as nitrogen gas (the most abundant gas in our atmosphere), but huge amounts of energy are required to reduce nitrogen gas into a form of nitrogen that plants can use. Fertilizer use has an additional environmental impact in that the nutrients that aren't taken up into the plants wash away to nearby land, rivers, and lakes, where they can cause considerable ecological problems.

There are many possible ways to approach these problems: tax fertilizers so they are used more judiciously; use a more expensive time-release formulation; monitor plants and soils to determine the optimal time of application for maximum uptake; and identify plants that are more efficient at nutrient uptake, perhaps by having a more efficient transport systems in the roots or a greater root area for uptake. All of these are important contributors and all will play a role in protecting our environmental health and maintaining agricultural productivity. One particularly interesting approach is to develop high-yielding crop varieties that are perennial rather than annual. Currently, our major crops are all annual, meaning the plant starts each growing season as a seed and produces roots, shoots, and seeds in a single growing season, then starts again from a seed the following year. This annual life cycle means that the root system is never allowed to get very large. By contrast, perennial plants grow for several years and have significantly larger root systems, which allows for increased nutrient and water uptake and also helps prevent topsoil erosion.

Pathogen Resistance

Pathogen stress drastically affects plant yields. There are a huge variety of organisms that want to feed on plants, including viruses, bacteria, fungi, nematode worms, insects, and herbivores. Some plants have evolved genetic resistance to certain pathogens, but in a sort of arms race, many pathogens have evolved ways around this resistance. Plant breeders are adept at keeping up in this arms race and are continually identifying resistant strains to cross with the high-yielding varieties. Occasionally, though, the pathogen really jumps ahead, and a major plant disease epidemic breaks out. For example, two such epidemics are occurring today.

Phytophthera infestans is a plant pathogen that has already made its mark on history, as the causal agent of the potato late blight disease that caused widespread crop failures in the 1840s. *P. infestans* spreads rapidly and can kill a potato plant within a week. Like the potatoes it infects, *P. infestans* originated in the mountains of South America. However, it didn't reach Europe until the 1840s, by which time the potato had become a staple crop in much of Europe. Widespread crop failures contributed to famine, death, and mass emigration. Subsequently, resistant varieties were identified, and a combination of genetic and chemical controls has kept *P. infestans* under control for over 150 years. Recently, one or more new strains of this pathogen have evolved that most potato varieties are not resistant to. Potato breeders are hard at work trying to identify new strains and new genes to confer resistance and protect this crop once again. Their efforts will be helped by the information derived from the newly completed genomic sequence of *P. infestans* and the first draft of the potato genome.

Similarly, the wheat pathogen *Puccinia graminis tritic*, the causal agent of wheat stem rust disease, has developed a mutant form (called Ug99) that is no longer resisted by the most widely grown wheat varieties. This pathogen has spread from eastern Africa into the Near East and Asia and currently threatens all of these important wheat-growing regions in which it can potentially cause a significant famine.

It would be nice to think that once a crop is harvested it is no longer vulnerable to pathogens, but unfortunately that is not the case. Seed crops must be meticulously stored to prevent losses from rotting, which nevertheless occurs with alarming frequency. Fruit and other high-water-content harvests are also vulnerable to postharvest losses due to cellular aging and damage as well as microbial pathogens. Postharvest losses are particularly difficult economically for farmers because the huge investment of resources and labor has already gone into producing the food that ultimately cannot be eaten or sold. This problem has many contributing solutions, including better management of storage facilities, more rapid distribution systems, and genetic improvements in plants to minimize these losses.

Improving Food Quality through Biofortification

Hunger and malnutrition usually coincide. Currently one billion people are chronically hungry, but twice that many suffer from iron deficiency. Our red blood cells need iron to transport blood through our bodies; iron deficiency causes weakness and fatigue. It's estimated that eradicating iron deficiency could improve adult productivity levels by as much as 20%. In children, iron deficiency contributes to developmental and growth defects as well as increased susceptibility to infection. Vitamin A deficiency affects one-quarter of the world's preschool-aged children and is an underlying contributor to the death of a million young children every year. Vitamin A deficiency leads to increased susceptibility to disease and blindness, as well as growth and mental retardation. Malnutrition disproportionately affects children, underlies half of all early childhood deaths, causes lifelong health problems for others, and it is totally preventable.

Many of the world's malnourished have limited access to meat and fresh green vegetables, important sources of iron and vitamin A. Many malnourished children eat mainly rice, which in its common polished form does not provide iron or vitamin A. Several varieties of rice with increased iron content have been developed by conventional breeding as well as transgenic approaches. High-iron-content rice has been shown to reduce anemia in humans. Vitamin A–enriched rice produced by transgenic methods has been developed, but its transgenic origins have hindered it from being distributed (see more on the regulatory obstacles to its dissemination at goldenrice.org). Other biofortified crops under development have increased levels of zinc, folate, and iodine, and a high-antioxidant tomato has recently been shown to reduce incidence of cancer in laboratory mice. These kinds of fortified food can particularly benefit people whose diet is by necessity very restricted due to poverty or the unavailability of a diverse diet.

Plants Are Sources of Medicines, Materials, and Nonfood Energy

Plants provide us with more than food; they are also a source of many important pharmaceutical products, wood, and fiber, and, increasingly, biorenewable replacements for petroleum-based plastics and energy.

Hundreds of naturally occurring plant compounds have beneficial effects on humans, ranging from the simple pleasure of vanilla and caffeine to life-saving tumor-suppressive drugs. Most of these compounds are produced by only one or a few species, as part of their chemical defense arsenal against pathogens. The chemical diversity of the plant kingdom is immense and largely unexplored. Many of the plants that produce the drugs we use today were identified as having healing properties hundreds or thousands of years ago. For example, the bark of the cinchona tree, which contains quinine, was used by indigenous Peruvians to treat malaria, and Chinese herbalists described a similar use of *Artemisia* more than 2000 years ago. Ethnobotanists work with indigenous populations to identify such plants and investigate their properties. Because pathogens can often develop resistance to effective drugs, sources of novel active compounds are constantly needed.

Plants are also being used for to produce other compounds for medicinal use, including antibodies, human proteins (e.g., insulin), and even vaccines. These are sometimes referred to as plant-derived pharmaceutical proteins, and the practice of making them as pharming. Some of these efforts are simply alternatives to other methods of protein production, replacing more expensive mammalian cell culture systems, whereas others exploit specific properties of plant cells. The edible vaccines are particularly exciting because they hold great promise for use in poor countries, where many children are not vaccinated against preventable diseases simply because of the financial cost. Traditional immunization programs require that the antigens are sterilely packaged and kept refrigerated until they are injected through a sterile syringe; all very costly procedures. Edible vaccines require no sterile or expensive handling because they are effective at promoting immunity when eaten. It won't be long before all children are protected from the devastating effects of cholera, smallpox, measles, malaria, plague, and hepatitis without ever seeing a needle.

Plant cells have a wall made predominantly of cellulose, a carbohydrate produced from glucose. Most animals are unable to digest cellulose into its sugar components, so cellulose-rich materials are particularly durable. Some plant cell walls, such as those found in woody tissues, also contain a glue-like substance, lignin, which cements the carbohydrates together. Humans have always used wood as a building material and source of shelter, and wood continues to be a major building material. Plant fibers are used for the production of paper (and before that, papyrus) and fabrics such as cotton, linen, and rayon. Scientists are developing plants that have improved fiber qualities or from which it is easier to extract usable fibers, both for traditional materials such as paper and cloth, but also for new, biorenewable alternatives to nonrenewable materials. For example, biocomposites, materials incorporating plant-based fibers in a plant-based matrix, are being developed as alternatives to petroleum and glass-fiber materials for use in the automotive and building industries. These new materials are being developed through collaborations between plant scientists, materials scientists, and chemists. Plastics derived from plant carbohydrates and oils are also being developed as alternatives to petroleum-based products.

Biofuels and bioenergy are terms that have become familiar to us through ongoing discussions in the news media and government agencies. Clearly, if the renewable energy stored in plants can be harnessed to sustainably replace nonrenewable energy sources like petroleum and coal, everybody will benefit. Traditionally, wood was burned to provide heat and light, but modern society requires different types of energy, including liquid fuel for automobiles. Plant sugars can be fermented into ethanol, which can then be mixed with gasoline; this approach works best when the source material is rich in sugars. For example, in Brazil, ethanol derived from sugarcane provides much of the country's liquid fuel needs; all of the gasoline sold in Brazil contains at least 25% bioethanol, and many cars can use fuel that is 85% ethanol (E85). Diesel engines can run on biodiesel fuels, produced from the oils extracted from plants, including rape, algae, and soybean.

Using edible plant materials for energy production could affect the price of food. Therefore, it has been recommended that bioenergy should only be derived from nonfood sources, such as perennial grasses, woody plants, and the stalks of crops after their seeds have been harvested. The energy in these materials is sequestered in the cellulose of the plant cell walls, and developing efficient ways to convert these to ethanol is a subject of considerable research effort. Identifying plants that are optimal for bioenergy production is also critical; *Miscanthus giganteus* is one such promising plant. It is a perennial, with deep roots that are efficient at water and nutrient uptake, and has an extremely fast rate of growth. It also grows in regions that are not well suited for food crops, so its production should not affect food availability or prices.

WHY STUDY PLANTS?

The study of plant biology has never been more important or more exciting. Genetic tools are enabling plant scientists to understand plants with ever-increasing levels of sophistication. This knowledge is making it possible to develop plants that are more efficient providers of the food, medicines, fibers, and raw materials upon which our human population is wholly dependent.

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ADDITIONAL RESOURCES (* INDICATES RESOURCES THAT DO NOT REQUIRE SUBSCRIPTION)

General Overview

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