PLANT MANAGEMENT SYSTEMS

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Summary

From plants, we derive the majority of our food and fiber as well as many of our fuels and medicines. Plant biotechnology advances promise to dramatically amplify the

utilization of plant resources in the future. Plant management systems that are both remarkable in production and undisruptive to natural ecosystems are required to satisfy the seemingly conflicting demands of world population growth and the need for environmental quality and sustainability. If overall plant production decreases or even plateaus, there will be intense pressure on marginal and environmentally sensitive land for food production. On the other hand, if intensive production techniques degrade the productivity of the current land base, increases in production, or even sustained production, will be in jeopardy. Managing and manipulating plants involves managing and manipulating ecosystems. Soil, air, water, nutrients, and hosts of associated living organisms are all impacted by plant management systems. Technologies (inorganic fertilizers, genetic modification, pesticides, etc.) should be employed not because they are available, but because they are necessary, they enhance or are relatively neutral to natural biological processes, and risks from their use are low. Diversity in management practices, genetic resources, economic systems, and cropping systems will help to enhance sustainable production. Highly productive and environmentally benign plant management systems of the future will likely entail a delicate balance of human-engineered and biological inputs. Integrated plant management systems that balance all of these demands will require a high degree of knowledge and expertise to successfully increase production and maintain environmental quality.

1. Introduction

Food and fiber, global population, environmental costs, societal anxiety, health of soil, water and air, the need to eat compared to the affluent’s desire for quality: all are of global importance and contribute to how plant management systems (PMS) have developed and function. Agricultural systems—required to feed the world, and to supply fiber, bio-fuels, medicines, nutraceuticals, and innovative bio-products—must balance conflicting societal demands and environmental challenges that are continually evolving in nature and complexity. Sustainability has emerged as the primary issue for all world systems, not least agriculture food systems.

Agro-environmental issues are not new to governments and crop producers. To begin with, the focus was on the conservation of the natural resource. More recently, the environmental challenges facing agriculture have broadened to include acceptable levels of environmental quality and quantity, as the agriculture sector has adopted new intensified production methods to meet the growing demand for agricultural products by society.

2. Nature’s Building Blocks

PMS require inputs of water, mineral nutrients, energy, and plants to function at a minimal scale and result in outputs that contribute to the wealth of individual farmers, regions, nations, and the global economy. With the exception of hydroponic systems (see *Greenhouse and Hydroponics Systems*), most systems require soil.

2.1 Energy

Sugar molecules are the result of the most important mechanism of energy capture in our biosphere: photosynthesis. Organisms with chlorophyll produce between 100 billion and 200 billion metric tons of sugar annually. Except for a few bacteria species that derive their energy from inorganic compounds, photosynthesis is the sole means of sustaining plant and animal life at any level. Fossil fuels represent the long-term storage of solar energy captured by green plants; they are generally non-renewable and inedible. Plants are integral participants in the cycles that sustain all ecosystems. Plants utilize light energy, CO_2, and H_2O and produce O_2 and carbohydrates, thereby regulating CO_2, H_2O, and O_2 cycles on our planet. In symbiotic associations with *Rhizobium* bacteria, many leguminous plants also reduce atmospheric nitrogen to forms utilized by all plants in the ecosystem.

Since plants function on solar energy, the management of plant systems will impact the capture and utilization of this energy by plants. The capture of the Sun's rays can be increased by expanding the leaf area of individual plants to capture more energy, increasing the volume of standing crops on a unit of land, and lengthening the time the crop is grown. Technology can improve PMS and more efficiently utilize the energy flow supplied by the Sun. However, this intervention in ecosystem processes should only be done in ways that allow for simultaneous protection of water and mineral cycles, as well as all organisms in the ecosystem. One cannot understand, protect, or exploit the basic resources and cycles in our biosphere without understanding how plants interact with those resources and cycles. PMS are not only important for our supply of food, fiber, fuel, and medicine, but they are also the tools that provide us with the means to influence all ecosystems and life cycles, including our own.

In PMS, water management (see *Water Management*), better yielding crop strains (see *Genetic Systems*), growing two or more crops on the same land in the same year (see *Multiple Cropping Systems*), and expanding acreage have all increased the capacity for humans to capture solar energy through photosynthesis. However, these energy gains have been offset by heavy use of non-renewable resources required to manufacture machinery, fertilizers, and pesticides and the fuel required to apply these resources. The origin of most of these resources used to capture solar energy is also solar energy.

2.2 Water

An understanding of the water cycle is required to be able to manage the natural water resource effectively. Water availability to humans is very limited in comparison to total volume, and access is difficult considering the variability in distribution and movement (see *Water Management*). Water cycles between Earth's surface and the atmosphere. In PMS, an effective water cycle provides a good air-to-water balance in the soil, enabling plant roots to readily absorb water with enough aeration to prevent anaerobic stress. Soil surface evaporation, runoff, and poor air-to-water balance results in low water use efficiency, poor crop health, and limited solar energy capture.

Effective precipitation in PMS is available for plant roots, soil microorganisms, insects, and other organisms and replenishes underground supplies. In an effective water cycle, cycling water among plants, soils, and the atmosphere is in equilibrium. Precipitation is required in the soil profile to fill soil pores at a rate that reduces losses to the atmosphere. On most cropland, excessive evaporation causes drought stress, while flooding causes anaerobic stress. In some rice systems, flooding is desirable for at least part of the production cycle.

If water supply is not adequate to maintain a minimum turgor pressure within cells at all stages of plant development, plant size is limited. The result is a reduction in plant development at the stage when the water stress occurs, such as less leaf area, fewer tillers (surviving or unformed), fewer spikelets or florets, or unfilled grain. Plants are programmed genetically to produce to the limits of their resources. Unlike most animals, plant size and development is very plastic. Different microenvironments can lead to neighboring plants of the same genotype with radically different morphology and/or size. The relative immobility of plants compared to animals enforces spatial restrictions on the immediate and adjacent resources to which they have access. With other resources unrestricted, the greater the access to water by plant roots, the larger the plant. Furthermore, the larger the plant, the greater the supply of water required to maintain cell turgor for continued growth and development. In resource limiting situations, seed production (producing and conserving genetic resources for the next generation) is enforced at the expense of maximum whole-plant growth.

Irrigation water management is common in PMS and requires knowledge of the water cycle in local landscapes (field scale). The scarcity of fresh water in the world behooves irrigators to efficiently manage water application. Water losses may occur when transporting from the source to the field or applying to the field, or through water storage efficiency in the soil and distribution on the field (see *Water Management*). Global irrigation accounts for most of the fresh water used in the world, and irrigation water efficiency is an appalling 37 % worldwide. Innovative drip irrigation systems have the potential to reduce water use by 60 % over flood irrigation and 25 % over sprinkler irrigation systems, a feat that may prove useful considering that future demands for water are likely to increase dramatically. When irrigation costs are fully considered (including opportunity costs for fresh water) and those full costs are exacted for each usage, more judicious and efficient irrigation systems will follow.

Standing crop residues can protect the soil surface from the negative impacts of precipitation and irrigation water (water erosion and soil crusting). Crop residues left on the soil surface, standing stubble, or a growing crop all reduce the impact of water falling on the soil surface by reducing runoff (soil and water) and the degradation of soil structure. Soil cover is generally not limiting in highly productive sub-humid or humid areas. Plant residues in those areas—if not over-harvested or destroyed by tillage, burning, or other means—are sufficient to maintain a protective cover. In arid and semi-arid environments where water is limiting, it is more challenging to retain sufficient soil cover, particularly in annual cropping systems.

Once water penetrates the soil, it is attracted to soil particles and moves downward at a rate determined by the soil’s inherent properties. In soils with impenetrable subsurface layers, excess water is often detrimental to plant growth. Well-aggregated soil that is high in organic matter (OM) provides a medium for an effective water cycle, where some water will reside in soil for prolonged periods. Under some PMS, low OM and poor soil structure results in surface evaporation and/or runoff. In other PMS, where root capacity is limited or not in place when water is available, the water is leached beyond the rooting zone into groundwater. Therefore, PMS must ensure that suitable amounts of OM are retained in the soil. The presence of animals and their associated activities may also promote healthy soils and effective water cycling (see *Livestock Management Systems*). Water does not act independently of soil, soil animals, plants, and plant nutrients. The level of water interaction with related system components contributes to the environmental sustainability or instability of the system. Humankind's dependency on high quality water supplies from healthy watersheds is directly associated with appropriate PMS. Therefore, environmental sustainability requires appropriate stewardship of PMS to supply healthy water to all organisms in the biosphere.

Excess water on agricultural land (precipitation, irrigation, saline seeps) can damage crops and soils and may require artificial drainage. Intuitively it would seem that an over-abundance of water would be more of a problem in humid and tropical areas; however, potential also exists for problems in the more arid and semi-arid areas if water is not managed properly. Indeed, some arid regions have severely reduced agricultural capacity due to water excesses in soil profiles. In terms of land capability, the amount of water received in a particular area is less important than how the water is managed. Benefits, environmental impacts, and ameliorative methods are described in detail in another article (see *Water Management*).

Water will continue to be required to grow food for the predicted 2–4 billion more people in the world over the next 25–50 years. It is possible to grow more food with existing water resources if methods are developed to increase the efficiency of water resources in rain fed and irrigated agriculture. The challenge will be to grow enough food for increased populations when water resources are limited, and agriculture water efficiency is low and already is highly exploited, particularly in the areas of the world where the population increase is greatest. The Food and Agriculture Organization (FAO) suggest that 84 % of all agricultural land is rain fed; even higher percentages are likely in semi-arid regions of developing countries. Improving rain fed agriculture in the latter areas will increase food production where food is required in large quantities. Improvements in rain fed areas will also reduce the dependency on fresh water sources for irrigation. Generally, agronomic and hydrological principles are available but poorly understood and applied in a water-scarce world.

2.3 Minerals

Plants capture soil nutrients during the uptake of water, and hence, both processes are closely linked. Nutrients, along with carbon dioxide in the air and energy captured from the sun, provide the raw building materials ultimately transformed and accumulated in the plant as dry matter. Plant management methods can drastically alter the recycling of nutrients by living organisms within the ecosystem. For example, PMS that substantially inhibit soil microbes or restrict their diversity not only endanger nutrient cycling, but could also reduce plant residue decomposition sufficiently to restrict normal planting operations. The mineral cycle is interconnected with water, energy capture, animal, and plant cycles. Consequently, events in one cycle will affect all of the others.

The principle of plants producing to the limits of the available water resources (see *Water*) also applies to mineral nutrients. At any stage of development, a plant will maximize its genetic potential if the necessary resources are not limiting. The larger the plant at any given stage of development, the greater the supply of materials needed for continued growth and development. Nutritional constraints are balanced with environmental constraints to distribute carbohydrates and produce dry matter in plant parts that will maximize the growth and survival success in any particular situation.

Plants take up nutrients through an extensive root system and bring nutrients from the soil to aboveground shoots. Although the goal in many PMS is to provide food, mainly from shallow-rooted crops such as corn or wheat and some legumes, some deep-rooted plants may be essential to the health of the whole plant and animal community. Figure 1 illustrates high and low diversity root system patterns. Nutrient retrieval from the entire soil volume not only is important for nutrient use efficiency, but also reduces nutrient leaching beyond plant root zones to groundwater and into the water cycle. In a given area, plant species diversity (with diverse rooting patterns) facilitates the efficient capture of nutrients whether they are recycled via soil organisms or applied as organic or inorganic inputs. Accordingly, continuous cropping of single species, or closely related species, may be detrimental to nutrient use efficiency and the environment.

In addition to species diversity, nutrient use efficiency and the prevention of nutrient runoff and leaching are facilitated when root systems extract nutrients over the entire growing season. Perennial species and multiple cropping (See *Multiple Cropping*) help ensure nutrient extraction over the whole season, but there are also good options in other cropping systems. Winter crops capture nutrients in the late fall and early spring, when many annual crops are not planted or are already harvested. Unfortunately, the dominance of summer annual cropping systems in most areas in the northern temperate zone leaves soils and their profiles subject to nutrient runoff and leaching in the late fall and early spring. Rotations that favor growth habit diversity (systems of annuals, winter crops, and perennials) and variable seeding and harvest dates will be most favorable for optimum nutrient use efficiency.

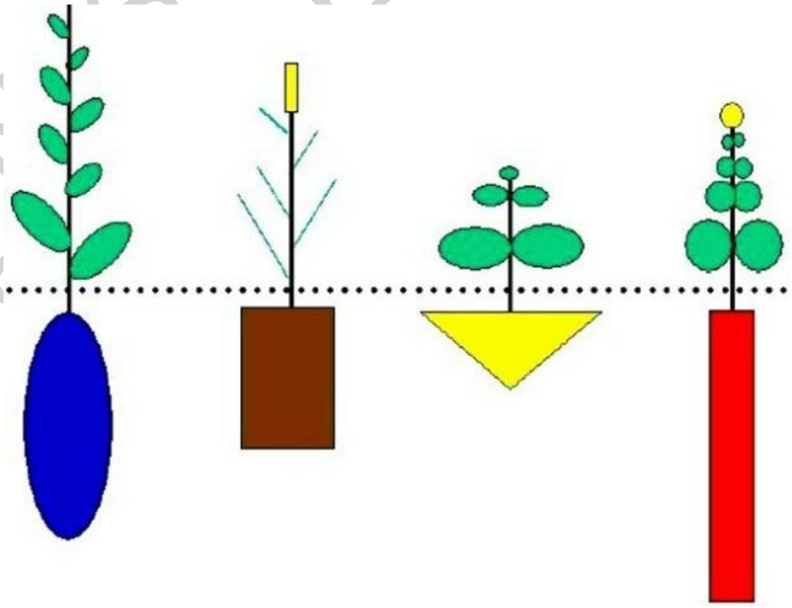

Figure 1. Plant communities with diverse root systems, or crop rotations that include crops with diverse root systems over time, will extract water and nutrients from the soil

profile most efficiently. Roots of various colors suggest the unique attributes and chemical compositions of roots from different plant species. In a given area, roots of many different species support a diverse community of soil macro- and micro-fauna. The latter makes it difficult for any single species of root pest (fungi, bacteria, insect, nematode, etc.) to dominate the soil organism community.

In the mineral cycle, leaving or returning crop residues after harvest returns minerals to the soil surface. Without the return of residues to the soil surface, the biological activity in the soil and soil OM are substantially reduced and long-term sustainability may be unachievable. Biological activity determines residue decomposition, and it should be encouraged in all PMS to improve the sustainability of the system and reduce dependence on commercial fertilizers.

Native prairies and forest systems function in the absence of tillage and commercial fertilizers. Soil organisms provide the "tillage" and the "fertilizer" through decomposition of plant material and dead roots and recycling of nutrients from previous growth. In these systems, the nutrients rarely leave the natural landscape. Topsoil is full of biological life that continues to turn over bound-up minerals to plant-available forms. Access to nutrients required for growth in PMS also requires a biologically active, living soil, with adequate aeration and energy to sustain an abundance of organisms in close proximity with water, nitrogen, oxygen, and carbon. In agricultural systems, PMS that support the survival of earthworms, arthropods and various soil organisms encourage the belowground distribution and cycling of nutrients by water and animal activity.

Unlike relatively closed systems in un-harvested native grasslands or forests, where nutrients are constantly recycled and removal is minimal, the PMS that provide the vast majority of our food remove nutrients from the field. Consequently, when growing food, nutrient replacement is essential for healthy soils. Several methods are utilized for replacing the nutrients required; these include biological nitrogen fixation, manure and organic amendments, composts, and inorganic fertilizers. The four major macronutrients (nitrogen, phosphorous, potassium, and sulfur) and the methods to replenish these nutrients are more fully described later in the text (see *Plant Nutrient Management*). Macronutrients are required in relatively large amounts for the manufacture, maintenance, and function of cells and tissues. Micronutrients are critical to key processes within cells and tissues and are required in only trace amounts. PMS designed to maximize the capture of nitrogen within the plant, store soil nitrogen in plant residue for future crop production, and minimize nitrogen losses contribute to a healthy living soil that is environmentally benign.

2.3.1 Importance of Surface Residues

The mineral cycle is influenced by whether crop residues are returned to the soil and the subsequent condition of the soil. PMS that return all unharvested crop residues, limit tillage, and utilize soil fauna for nutrient cycling and soil health are sustainable. A healthy soil protected by crop residues provides an environment that contributes to species diversity and improves the physical characteristics of the soil. PMS that leave the soil surface exposed not only risk wind and water erosion, but also may cause soil crusts to form after heavy rainfall. Bare, crusty soil is a harsh microenvironment where biological activity has little chance to prosper and the breakdown and recycling of nutrients occurs slowly at best. Such a crusted surface limits air exchange between the soil (and its organisms) and the atmosphere. The negative consequences of soil crusting ripple throughout the microenvironment, and soil OM and structure are decreased with further declines in air exchange. The regressive cycle continues on soils with fewer plants, less soil cover, and more bare crusted soil. There is little chance that these soils can maintain healthy plants that will utilize the available water and nutrients. Excessive water and nutrients then lead to further soil and environmental degradation.

There are advantages to both food production and the environment if PMS parallel the patterns of resource utilization that occur in natural ecosystems in similar areas. Although it is not possible to fully mimic natural ecosystems in agricultural food production systems, the integration of annual and perennial vegetation, rotation of annual and perennial crops, and conservation agriculture will enhance surface residues and facilitate nutrient cycling in agriculture landscapes.

Facilitating nutrient cycling in agriculture landscapes to sustain intensive PMS remains a considerable challenge for the future, particularly since intensification will be required to feed the growing population. In addition to reducing greenhouse gas production and other forms of pollution, improving the resource efficiency will increase profitability and conserve natural resources. The real challenge is therefore to develop soil building production methods that are more productive. Essentially this means improving the efficiency with which nutrients, water, and other inputs are utilized and returned to the production system.

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Biographical Sketches

George W. Clayton received a B.S. in agriculture and an M.S. in agriculture at the University of Manitoba and a Ph.D. in agronomy at the University of Saskatchewan. George spent the past ten years as the section head of the Plant and Soil Research Section at the Lacombe/Beaverlodge Agriculture and Agri-Food Research (AAFC) Centers.. He conducted a research program in tillage and cropping systems agronomy that spans central Alberta to the North Peace River region. He is very active in extension activities, reporting research results to producers and other scientists. George has conducted agronomic trials on applying granular inoculant in field pea and is currently conducting integrated agronomic trials with barley, field pea, and canola in conjunction with weed scientists, pathologists, and others in Western Canada. His research emphasis was to combine agronomic factors as the first line of defense against weeds, insects, and disease. George is currently the National Program Director for Sustainable Production Systems with AAFC Research Branch.

K. Neil Harker received a B.S. degree in agronomy from the University of Alberta, an M.S. degree in weed science at the University of Minnesota, and a Ph.D. in weed physiology at the University of Guelph. In 1985 Neil joined Agriculture and Agri-Food Canada at Lacombe as a weed scientist. Neil has a 100 % research appointment, but he also spends some time extending research results to crop specialists and producers. Since 2000, Neil has held an Adjunct Professor appointment at the University of Alberta. His research is focused on weeds in direct-seeded, integrated crop management systems. The majority of his projects involve collaboration with agronomists, plant pathologists, soil microbiologists, entomologists and economists. Neil's major research focus is combining optimal weed management practices with key agronomic factors in an attempt to improve farm profits and sustainability. Other projects include herbicide detections in groundwater and rainfall, the study of early weed removal, and basic weed biology.