PS&C
Prairie Soils &
Crops Journal

Principles of Crop Production

David J. Connor, Emeritus Professor of Agriculture, Melbourne School of Land and Environment, University of Melbourne, Victoria 3010, Australia (djconnor@unimelb.edu.au)

Summary

Plants are autotrophic and therefore they fix the energy of the sun and manufacture food from simple inorganic substances for almost all other organisms through photosynthesis. Crop plants have a wide range of development and growth responses to sunlight, day length, temperature, nutrients, and water supply. Farmers do not, however, choose plants as crops for optimum adaptation to individual environments, but those that are preferred food, as in developing countries, or to meet market requirements, including global trade. In consequence, crops are managed to withstand environmental stresses. Socio-economic forces drive change in agriculture that is currently challenged to increase production by 70% to feed 9.2 billion by 2050.

Introduction

Green plants occupy a special place among all living things on earth, the biosphere, because, uniquely, through their greenness, they connect earth to an external source of energy, the sun. They 'pack' this energy into sugars or carbohydrates (CHOs) that become the basis of all other living things, except for some chemoautotrophic organisms, principally bacteria. This puts them at first position on the food chain that includes all other organisms: humans, carnivorous and omnivorous creatures, and decomposers. The carbon-based organic compounds that plants accumulate in vegetative structures and storage organs are, directly or indirectly, food for the vast majority of organisms in the biosphere. Plants alone are independent of other organisms by fixing carbon (C) from atmospheric carbon dioxide (CO_2) and producing oxygen (O_2) as well as carbohydrates (CHOs). They are dependent only on mineral nutrients and water they absorb from soil for the internal chemistry of their metabolism. The unique process by which plants fix solar energy that then moves through the entire food chain until the C is returned as CO_2 to the atmosphere is called photosynthesis

Humans are a part of the food chain and while our ancient ancestors collected plants and hunted animals, we now, with technological development and a large and growing population, secure our food supply and that of our domestic animals by growing plants specifically for those purposes. This essay is written to introduce this important topic of the role of crops in food supply for human existence and survival. While it is written for an agricultural audience, the general principles are relevant to all. This is true if only to counter a view, held by many urban dwellers, now comprising 50% of world population, that food originates in supermarkets.

The essay is presented in two major sections, using a structure recommended by my Australian colleague David Smith as in his book "Rain and Shine"[3]. First is "How plants grow". David insists we keep the basics in mind at all times using understanding of How Plants Grow as a critical backdrop to farming, which is the second part of the essay, "How we Grow Plants". Backing these two sections is a vast body of scientific work that cannot be included here but is available to interested readers in books like "Crop Ecology: Productivity and Management in Agricultural Systems "[1].

How plants grow

Seed germination

Small though they often are, seeds are fascinating entities. As well as containing the 'germ' – the life package of genes/chromosomes that define the plant – they contain precursor chemicals that set growth and cell differentiation in train, and a small supply of the CHOs mentioned above. Thus, when seeds imbibe water, chemical and osmotic forces begin to operate so that embryonic cells divide and tissues of root and shoot begin to grow, recognizable in a day or two. The process is germination and seedlings can continue growth until the chemical reserves provided to them by mother plants are exhausted. The beginnings of a sense of geo-positioning in the world provided by a seed's genetic code are almost immediately obvious. First, root systems grow downwards and then shoot systems, in some species carrying the seed, grow upwards, pushing through any soil cover or litter into the atmosphere.

For individual seedlings, there are two critical steps that must be achieved before reserves are exhausted. First, emergence from the soil and expansion of seedling leaves and secondly, penetration of the developing root system into soil where it can absorb water and essential mineral nutrients. Then occurs the greatest miracle after life itself, seedling leaves turn green in the presence of sunlight by formation of chlorophyll and connect the plant to the power of the Sun. The plant is then an established properly functioning independent organism that can accumulate C-based compounds and the plant body can grow. Life on earth can now go on! These processes should be constantly on show to all children in primary school classrooms.

Continuing growth, increase in size and leaf area, requires a continuous supply of CHOs from photosynthesis in new expanding leaves and water and nutrients absorbed from soil by roots. But there is much more to growth than this, however. Plants grow by forming new organs, viz. roots, stems, seeds, and other storage organs. These processes are controlled by environmental responses that, like geotropism, come embedded in the genetic code. Thus, most plants will only flower and produce seed if conditions of temperature and day length are appropriate, and these conditions vary widely from species to species. These responses are adaptations that have evolved to ensure that, once established, development will normally lead to flowering, pollination, and seed production, thus maintaining the existence of the species. Survival of successful plants drives evolutionary adaptation. Most plants require pollination from another member of the species so the new seedling is 'after its kind' but not identical to either parent – therein lays scope for evolution – and human controlled plant breeding also.

Development and flowering

Some plants are perennial and live for a number of years, in the case of some trees, for thousands. Many are annual and germinate when conditions are suitable for growth, have a herbage producing stage, then flower and set seed, usually avoiding the season when growing is difficult – too dry, too hot, or too cold. Thus flowering is a hugely important stage in plant development. It follows changes in activity of some buds (meristems) found at ends of shoots, and in axils of leaves and branches, to form flowers rather than more leaves. These changes are mediated by chemical signals sent to these meristems, in response to temperature or changes in day length, or a combination of the two. For example, wheat and canola respond to increasing day length, so are long-day plants that flower in Spring, though some cultivars require a chilling period (low temperature) before they can respond to increasing day length. So we have "winter" and "spring" types, suited to different sowing times depending upon the temperature regime. This terminology can be confusing, however. Winter types are always sown in Autumn, but in places where Winter is not severe, spring types can be sown also: where Winter is too severe for plant survival, however, only spring types sown in Spring can be successful.

The location of flower buds on plants is also important because it has an effect on growth strategies and thence seed production. Wheat and canola flower on terminal shoots – we call it 'determinate', field peas flower in axils – we call that 'indeterminate'. Each flowering trait has its own advantages and disadvantages. For example, determinate crops are vulnerable to unusual, isolated, periods of stress during flowering. In wheat, for example, a single stress from frost or heat can abort most flowers, so that grain yield is at best very small. In contrast, prolonged flowering of indeterminate crops means that such short stress periods of frost or heat or water shortage have less effect on seed yield. To complicate the matter further, with indeterminate plants there is significant competition for assimilates (CHOs) between growth of seed and further vegetative parts. In determinate plants, however, once seed is set the bulk of assimilate goes to seed growth. Thus, where plants are growing under resource-limiting conditions determinate plants that make a sharp transition in growth pattern at the best time – i.e. the "optimum switchover" from vegetative to reproductive growth - will yield better. By contrast in indeterminate plants, vegetative material increases as yield increases and partition of growth between vegetative and reproductive parts is not optimal for high yield.

Photosynthesis

Photosynthesis is the process of incorporating CO_2 into CHOs in chloroplasts of green leaves. Though the beginning and end points are the same, green plants, all of which have evolved from simple algae, have one of three systems of photosynthesis with different combinations of chemical steps and associated plant anatomy. The most common is the original algal C3 system (so named to recognize the chemical structure of the first product of photosynthesis), then two evolved variants called C4 or CAM, respectively. Crop plants are mainly C3 species.

All leaves have stomates (pores) through which CO_2 diffuses when photosynthesizing leaves reduce internal CO_2 below atmospheric concentration. In C3 plants, arrangement of internal cells means that movement of CO_2 into chloroplasts, where photosynthesis occurs, is slow. In C4 plants, by contrast, CO_2 is captured by an enzyme on entry and transported as C4 acids to chloroplasts in specialized cells that surround vascular traces. There, CO_2 is released in high concentration and enters C3 photosynthesis. The result is that C4 plants have higher rates of photosynthesis than C3 plants. This system also works better than C3 at high temperature so, unsurprisingly, most C4 crops are found naturally in tropical and subtropical climates. For example wheat, canola and field pea are C3 plants while corn and green foxtail are C4 plants.

The third system, crassulacean acid metabolism, CAM for short, is named after a family of succulent plants, the Crassulaceae, in which it predominates. This adaptation from C3 is one of timing. Stomates are closed during day time but open at night when CO_2 enters and is concentrated in C4 acids in large succulent cells. During daytime, CO_2 is released and enters C3 photosynthesis. Photosynthetic capacity is limited by capacity for acid storage but some CAM plants also open stomates during the day and that increases photosynthesis. Pineapple is the most important CAM plant grown as a crop.

Water relations

As we know, plants require a continuous water supply. Although a small amount is used in chemical transformations, most is lost by evaporation from wet cells inside leaves and then by diffusion through stomates to the dry atmosphere beyond, in a process known as transpiration. Stomates must open to allow CO_2 entry to support photosynthesis so transpiration is an inescapable result of plant morphology and metabolism. Plant growth is a continuing exchange with the atmosphere of water for CO_2 while plants seek to maintain water supply and turgor by extracting water from soil. The ratio of water loss:biomass gain is considerable and is in the range 800–1000:1. Since plants colonized land, evolution has presumably been seeking improvement in these processes, with limited but valuable results, such as in selection of C4 and CAM types. In CAM plants, the fact that stomates are mostly closed in daytime greatly reduces water loss so that the ratio of water loss to CO_2 gain over a daily period is much less than in C3 and also in C4 systems. Soils vary greatly in water holding capacity and plants differ significantly in rooting habit – depth, type e.g. taproots and fibrous roots - and ability to withdraw water from soil. They also vary in ability to control loss of water from leaves, owing to differences in size, shape and epidermal wax, and frequency and behavior of stomates. Control of water loss is always made at the expense of CO_2 uptake for growth. For crops, flow of water from soil to atmosphere through plants is accompanied by direct evaporation of water from soil, particularly when the surface is wet and unprotected by foliage or mulch. This evaporation, which may consume as much of 50% of water loss in annual crops, together with transpiration through plants, is summed in the term evapotranspiration. Reduction of soil evaporation saves water for transpiration so more plant growth can be supported.

Nutrition

Plant growth is a complex of chemical reactions that requires a continuing supply of essential mineral nutrients absorbed from soil by root systems. These nutrients are required in differing amounts, depending upon their roles in plant metabolism, so it is usual to distinguish between those required in large amounts, the macronutrients (N, P, K, S, Ca, Mg) from others in smaller amounts, the micronutrients (Si, Fe, Zn, Cu, Mn, Mo, B, Ni, Co, Cl). Macronutrients occupy central roles in growth, N in photosynthesis and protein metabolism, P in energy transfers, and K in osmotic relations of cells. Micronutrients are involved in a wide range of metabolic reactions. Fe, together with Mg, are critical elements in the structure and operation of chlorophyll and hence in photosynthesis. Cu and Mn are important for N-fixing bacteria that grow symbiotically with legumes.

Many people do not recognize that plant growth is essentially an extractive process taking minerals from the soil, the exact amount varying from plant to plant, amount of growth and stage of maturity. These minerals are in the soil because of break down of the parent rock, or through deposition by dust and/or water. Each plant takes some, and under continued cropping, extraction soon exceeds any new supply. In nature, without human intervention all nutrients are returned to the system but in agriculture different amounts are extracted according to the composition of the harvested yield and its export. One interesting recent change, increasingly common in some countries for energy supply, has been harvesting of cereal straw as well as grain, leading to an additional large extraction of nutrients, notably of K. Another interesting aspect is that though nutrients are ideally available in balanced amounts required by growing plants, there can be absorption and storage for later use during the growth cycle. Thus, in annual crop plants, N for construction of grain protein, more important in legumes and oilseeds that in cereals, is mobilized from chlorophyll in senescing leaves. Thus breeding for high yield in crop plants must keep in mind this evolutionary adaptation: the more rapidly N is extracted from leaves for grain growth, the less active leaf area remains for photosynthesis and assimilate production.

Nitrogen is a very special nutrient and there has been much emphasis on it in crop research and in programs like the Green Revolution. Not only is N required in great amounts in plants but it is important through its relationship with the organic material of soil and chemical transformations by microbial activity there – and, ultimately with any sequestration of carbon in soils. The N content of decaying plant material is transformed to available, soluble, mineral form nitrate (NO_3^-) – but this is vulnerable to loss by leaching to depth as well as gaseous loss, mostly as N_2 to the atmosphere. The major source of N in natural systems is from legumes that fix N_2 in symbiotic relationships with bacteria, mostly in root nodules. In agriculture this source is important but is complemented by addition of N fertilizer, some mined, but mostly extracted from the atmosphere using natural gas using the Haber-Bosch industrial process.

How we grow plants

This leads us to a fairly brief discussion of human intervention in the above processes.

The change from hunter/gatherers to farming, even only as subsistence, was a logical one**.** Imagine a woman gathering food a long way from her cave sees a plant with a lot of fruit, picks some and it tastes good - better than any others she has tasted. Being a thinking person (that's what defines a human) she keeps the seed and uses her digging stick to bury it in soil nearer the cave, realizing this will mean a shorter walk to pick fruit in a year or two. The plant grows, and she is pleased. She protects her garden plants and to maintain their productivity removes others that crowd them. She and her family have noticed that faeces and urine are beneficial for plant growth, so they deposit them on the earth near plants. Here we see the beginnings of plant selection, soil cultivation, plant propagation, land clearing, and using manures, all in the cause of better production by plants and human convenience, “The beginning of agriculture”.

In this way, subsistence farmers intervene in nature to grow more of the plants they like to eat or need for other uses. In the developed world, farmers grow plants that meet their economic requirements by reasons of price for product or cost of production. In this they compete for markets with other farmers, often in distant places. It is a fallacy to think that farmers simply grow the crops that are best suited to their biophysical environment. In fact, they select from plants that are sufficiently adapted to the environment (temperature, rainfall, evaporative demand) and manage them to avoid stresses that would seriously reduce yield. They do this by growing crops in sequences to make best use of biological interactions between plants of different types while also applying agrochemicals, when needed, to minimize risk of failure from low fertility and invasion by weeds, pests and diseases.

Cropping strategies

On individual farms, the sequences of crops that are grown define the cropping strategy chosen to meet economic and environmental objectives. Common features of the Prairie Zone now are sequences of cereal crops such as wheat and barley, with oil seeds such as canola and sunflower, and the legumes, field pea, lentil, and chickpea. Growing each particular crop means something different in terms of nutrient requirements, response to stresses, competitive ability with weeds, and susceptibility to herbicides applied and to their residues. Cereals are less extractive of nutrients than oilseeds or legumes and legumes fix nitrogen reducing the demand for N fertilizer. Stubble protects soil from erosion and evaporation, canola stubble inhibits root diseases of wheat, and so on.

The cropping strategy was not always like this. As in other parts of the world, prairie cropping systems are continuously evolving. The first settlers commenced with continuous cereals because that was the technology settlers brought with them. As yields declined they introduced a biennial cropping sequence with an alternate (summer) fallow. Yields increased at first but gradually fell as fertility was extracted, and there was serious soil loss by wind and water erosion during sequences of years of low rainfall. New farming techniques and machinery enabled mulch farming to protect summer fallows, but they too have largely been replaced. Research has defined the more important determinants of yield: control of weed burden and manipulation of the N cycle to optimise availability. In due course both were seen to be aspects of responses to fallowing (along with some soil moisture carryover), and it was realised the effects could be better and more economically achieved by using herbicides and N fertilizer or legume crops. Fallowing is now restricted to low rainfall areas where its contribution to water storage is aided by herbicides rather than tillage to control weeds.

Now with continuous cropping using reduced-tillage, even no-till techniques (conservation farming), soil organic matter and structure are being restored, and costs of land management and crop establishment greatly reduced. Machinery is larger and more precise so more of the operations can be completed with near optimal timing. Standing stubble protects soil from erosion and retains snow until Spring when crops are sown. Last year's stubble means seedlings from precision-sown seed are protected during establishment as they emerge between rows of stubble. Fertilizers are applied as required and placed carefully relative to seed in appropriate quantities and formulations for most effective response. Changes to the systems continue as farmers adopt technology to adapt to changing environmental and economic conditions. The origins of change are often found in tactical variations in management as farmers seek to provide the best conditions for their crops allowing for year-to-year variability in weather and markets.

Tactical management

Measurement and technology and seasonal climate forecasts provide opportunities to better match crop performance with seasonal environmental conditions. This can either take advantage of high yield potential in some years or reduce costs when low yields are inevitable. Note we refer to cropping sequences and not "crop rotations" because that previously common term usually signified a specified, unbreakable sequence of crops. Tactical variation can start with adjustment to cropping sequence at sowing. Early or late start of season provides opportunity for change of cultivar or crop. Low content of water in the soil at sowing signals likelihood of low yield and inputs can be varied accordingly. Low nitrogen at sowing signals need for fertilizer appropriate to water supply. In-crop measurements of soil water and crop N content, or related variables of leaf colour and tiller number, can provide the basis for late fertilizer application, or equally abandonment and diversion of crops to hay or silage. Herbicide applications can be adjusted to weed counts and specific weed populations that emerge with crops. Weather and short-term climate forecasts can be combined with crop models to predict outcomes as a basis for overall management. Farmers need to consider many issues to make the decisions that determine the viability of their cropping enterprises.

Finally then, one of the great principles of crop production is that there is much more to it than adaptation to the biophysical environment in which crops grow. Understanding the basics of plant growth is an important beginning, but successful cropping is a game of measurement and decision-making that aims to balance odds in favour of farmers. Technology and management skill are essential if farmers are to conquer the challenge of variable climatic and economic environments.

Towards 2050

There are great challenges ahead for cropping and crop production, and continuing need for new knowledge and technology. The world population that is now 7 billion is expected to rise to 9.2 billion by 2050. That introduces the challenge to increase current food production by 70% because almost 1 billion people are currently underfed. Moreover, the challenge must be met on essentially the present cropping area of 1500 Mha because there is little opportunity for increase in the face of competition for nature conservation and other uses[2]. This large increase in crop production can only be achieved with combinations of greater crop yields and more intensive cropping adapted to local conditions and availability of inputs. Farming systems are dynamic and continuously adapting to changing ecological, environmental and social conditions, while achieving greater production and resource-use efficiency by application of science and technology.

The word sustainability is used loosely without useful definition. In the framework used in this essay, sustainable agriculture is defined as whether society is prepared to allocate enough resources to define problems, research them to find solutions in a reasonable time frame, and ensure adaptive remediation by the farmers.

The solution to "feed and green" the world in 2050 is to support this evolution more strongly by providing farmers with necessary information, inputs, and recognition. The challenge is, however, great. Irrigation, necessary to increase cropping intensity in many areas cannot be extended much more widely than at present, and it is uncertain if the current rate of crop yield increase can be maintained. Society needs greater recognition of food-supply problems, issues of food waste generally, and overconsumption in some societies. It must be prepared to increase funding and support for agricultural research to support the competent and innovative farmers in developed nations.

References

1. Connor, D.J. Loomis, R.S and Cassman, K.G. 2011. Crop Ecology: Production and Management in Agricultural Production Systems. CUP, Cambridge, UK.
2. Connor, D.J. and Mínguez, M. I. 2012. Evolution not revolution of farming systems will best feed and green the world. Global Food Security 1:106-113.
3. Smith, D. 2012. Rain and Shine: A Simple Guide to how Plants Grow. Connor-Court Publishing, Ballan, Australia.