Chapter 1
Agriculture and Agricultural Systems

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Abstract Crop Ecology deals with agricultural ecosystems that are manipulated by man to funnel the maximum energy into usable products (food and raw materials). Agricultural ecosystems show normally low biodiversity, low autonomy and a short trophic chain. The main features of farming systems are productivity, stability, resilience, and sustainability, the latter indicating the ability to maintain a certain level of production indefinitely. Production of agricultural systems requires inputs of matter, energy and information. Normally the economic optimum provision of inputs is below that necessary to achieve maximum production. Various parameters have been defined to characterize the productivity of agricultural systems (potential yield, attainable yield, actual yield).

Agricultural activity is characterized by uncertainty due to numerous environmental and economic factors. Faced with uncertainty, farmers' decisions are focused on avoiding risk and that may lead to losing opportunities. To make rational decisions the farmer has access to many sources of information, ranging from their own experience to research/technology transfer. The current trend is to improve the acquisition, sources, and the use of information on the agricultural system for improved decision-making.

1.1 Introduction

According to recent FAO statistics, agriculture occupies 28 % of the land area of the Earth, with 30 % devoted to crops and 70 % to pastures. Broadly, the cultivated area is less than 10 % of the total land area, encompassing around 1500 million ha largely unchanged since 1960, as expansion of new cultivated land has been offset

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by the disappearance of arable land due mostly to urbanization and to irreversible soil degradation. Of this area, 90 % is devoted to annual crops and 10 % to perennial crops. Irrigated lands occupy more than 300 Mha, representing 17 % of the cultivated area. Cereals are the dominant crops representing nearly 60 % of the total cropped area. In fact, although more than 7000 plant species are used in agriculture, only about 120 are considered important, and more than 90 % of the calories consumed by humans today come from less than 30 species. This does not mean that agricultural biodiversity is low, because there are germplasm collections harboring many thousands of different genotypes for all the main crop species.

Farming allows man to produce food and other products by managing and manipulating the trophic webs of ecosystems (Box 1.1). Agriculture is a set of human interventions that alter ecosystems to maximize the yield of the desired product and minimize energy losses along trophic chains. The science and technology of producing and using plants for human use is Agronomy. It deals with the exploitation by man of terrestrial ecosystems and has, therefore, its roots in ecology. The ecosystems modified by agriculture are called agroecosystems and the science that deals with their study is Crop Ecology. An agroecosystem is an ecosystem managed by man with the ultimate goal of producing food and other goods and services derived from agriculture. Population pressure has reduced the area of ecosystems free of human intervention. However, there are reserves, forests and other areas that may be called natural ecosystems, which are generally characterized by higher biodiversity, longer trophic chains and higher autonomy than agroecosystems.

The agroecosystem is characterized by the presence of a lower number of species than the natural ecosystem. This lower diversity is a result of the need to reduce energy losses along trophic chains in agricultural ecosystems, which aim to remove all unwanted energy transfers (to parasites, pathogens or plants which compete with the crop) and is usually associated with a shortening of the trophic chain. The energy autonomy of agroecosystems is relatively low because they depend on inputs of materials, energy and information provided by humans.

The unit of study in Crop Ecology is the field or plot. A community of plants, along with management practices (e.g. tillage method, rotation, etc.) located on a field is called cropping system. At this level one can analyze the production processes of plants, their relationships with the soil and their dependence on the aerial environment. By observing the same plot for several years we can analyze the effects of rotation, tillage practices or crop residue management on soil properties and resulting yields, as they are affected by the use of resources such as water and nutrients. Economic analyses or determining manpower needs are often made at the plot scale. A farm represents a single management unit constituted by a number of fields or plots.

At a higher level of organization, the cropping system is part of a farming system where other elements (e.g. livestock) are also managed by the farmer providing inputs to the crops or using crop products. The different crops and management practices prevalent in a given area, are called agricultural systems at a regional scale.

Agriculture, like all human activities, has known successes and failures throughout its history. Today agriculture produces enough food for the vast majority of the world population, despite the unprecedented population growth experienced over the last 50 years. However, it has also negative environmental impacts such as soil degradation and water pollution from the use of fertilizers and pesticides, excessive use of water resources, and the reduction of biodiversity. Furthermore, other sectors of society are very sensitive to a diverse set of problems created by agriculture, notably those related to food safety and to the threats to natural ecosystems.

Box 1.1 Ecology and Ecosystems

Ecology is the science that studies the relationships between organisms and their environment. The environment is the set of biotic and abiotic factors affecting growth, reproduction or mortality of organisms. Environmental factors may also be divided into resources when the factor is directly consumed by the organism (e.g. a nutrient) or regulators, when they affect the rate of use of resources (e.g. temperature).

An ecosystem is a group of organisms and the environment that coincide in time and space. The ecosystem is the fundamental unit of study of ecology. The organisms in an ecosystem are interrelated by flows of energy and materials. The dimensional characterization of the energy flows in the ecosystem is called the trophic chain. The primary source of energy is solar radiation, the driving force of life on Earth. Primary producers fix solar energy through photosynthesis, transforming it into usable energy that will move along the trophic chains. Over millions of years, the man has obtained the energy required for living from different trophic chains, by hunting and by gathering edible plants until 10,000 years ago, when agriculture was invented.

1.2 Characteristics of Agricultural Systems

The primary objective of farming is the production of sufficient food and other goods and services so that the farm stays viable. Therefore, a key feature of farming systems is their productivity, defined as output per unit of resource used, commonly referred to the cultivated area, which is the primary limiting factor of agriculture. Thus, productivity is defined as the yield of usable product per unit area but can be applied to other natural or artificial inputs as radiation, water, nutrients or labor, which are also typically measured per unit of area. The productivity level further serves as an indirect measure of the efficiency with which these inputs are used.

When characterizing agricultural systems, the term efficiency is often used to define the ratios of crop productivity and certain inputs. For example, efficiency of water use is defined as the ratio of yield to the volume of water used, but it would be more correct to speak of the productivity of water or nutrients, expressed as kg/m^3 water or kg/kg nutrient. In engineering, efficiency is the ratio between the output and the input of any entity in a system, for example, the energy supplied to an engine.

Besides productivity and efficiency there are other important properties of agricultural systems. Yields may vary from year to year by weather and other causes. The term stability refers to the magnitude of these oscillations. The lack of stability causes fluctuations in production that threaten the persistence of agricultural systems. This is particularly true when there are sequences of successive years of low yields that may have a catastrophic effect on their economic viability. Related to the fluctuations in productivity, there is another feature termed resilience which is defined as the capacity of the system to recover from a catastrophic event, for example a drought. High resilience is a desirable property of agroecosystems.

Another feature of farming systems is their sustainability which indicates the ability to maintain a certain level of production indefinitely. This feature stems from the concept of sustainable development, a development model that proposes economic growth without adversely affecting the opportunities of future generations. A farming system is considered sustainable when it is economically viable and socially acceptable, however, one must define the time frame, because what is feasible and acceptable today may not be so in the future. Thus in agricultural systems it would be more correct to speak of the degree of sustainability: a system will be more sustainable when its exploitation does not degrade the quality of water and soil resources, and when current management practices do not affect the productivity and viability of the system in the future. The improvement the sustainability should be based on two objectives: reducing or eliminating, if possible, the negative environmental effects of agriculture while maintaining high productivity. Decades of intensive production in many agricultural systems have caused negative environmental effects and have created awareness of the need to focus on the sustainability of the agricultural systems, leading to a debate about developing new forms of agriculture that ensure economic and ecological sustainability.

1.3 Management of Agricultural Systems

The strategy of agriculture is to manipulate the environment and the plant community to optimize the yield of goods useful to mankind. This involves establishing communities (crops or pastures) dominated by species that distribute a large proportion of the primary production to usable organs or materials. In addition, the farmer tries to minimize system losses due to insects, diseases and weeds.

Farmers have numerous management tools to control their crops, such as tillage for weed removal and seedbed preparation, choice of species and cultivars, sowing date and sowing density, application of fertilizers and pesticides, etc. External factors such as climate and markets are difficult to predict so the flexibility in managing the crop is very important to minimize the risk of crop failure or of economic losses in the farm. For example, an application of fertilizer may be reduced or waived if the rainfall is very low or if the expected price of the product is very low.

In general, for many resources the response curve of yield versus input level is curvilinear and the maximum profit is obtained at a level of resources below (but not far from) that required for maximum yield. This is because of the synergies that occur among inputs and of the addition of fixed costs, which make low input strategies generally inefficient. The more productive and more profitable farms are those that use resource levels which are commensurate with the production target, without any input clearly limiting yield. For example, there is little point to provide additional water as irrigation if the additional quantities of fertilizer required to realize the targeted yield are not provided.

Example 1.1 The response of a wheat crop to N fertilizer in a rainfed Mediterranean area is shown in Table 1.1. In this case the highest yield is achieved using 250 kg of fertilizer N per hectare. However, the economic optimum is achieved with an application of 200 kg N/ha. We can also see that a very limited use of resources leads to worse economic performance than overuse.

Table 1.1 Analysis of the response of a cereal crop to N fertilizer applied. The selling price is 0.25 €/kg, the fertilizer cost is 0.80 €/kg and the fixed cost is 200 €/ha

N applied	Yield	Income	N cost	Income – N cost	Net profit
kg N/ha	kg/ha	€/ha			
0	1200	300	0	300	100
50	1929	482	40	442	242
100	2329	582	80	502	302
150	2558	640	120	520	320
200	2883	721	160	561	361
250	3020	755	200	555	355

The criteria for managing agricultural systems must take into account many factors that are affected by farmer decisions. Not only plant and animal production processes are important, as are economic objectives, but also the effects on soils, water, animal welfare and human health, landscape and biodiversity, among others, have to be considered. All these items have a different weight depending on the farming system under consideration, although, as in any other business, when the farm is not dedicated to the subsistence of the owner, it is handled essentially based on economic criteria. Nevertheless, there are many facets to the management of farming systems. In areas where the ratio population/arable land and input prices are low (e.g. USA and Australia), the emphasis is on maximizing profit per unit of labor. In Northern and Central Europe and in Japan, where arable land is the limiting factor and input prices and wages are high, farmers tend to maximize productivity per unit area. Similar goals are pursued in the agriculture of China and India due to the limited availability of land per farm. These situations contrast with those of many poor countries where labor is abundant and access to inputs and capital is scarce.

Crop yields are close to their maximum potential only in a few areas (as in farms of Japan and Northern Europe), so that the average yields of agricultural systems are generally poor indicators of potential productivity. Actual yields lie in a broad interval from zero (crop failure) to a maximum attainable level which is only limited by the aerial environment (solar radiation and temperature regime), this yield level is called potential yield. Actual yield is defined as the average yield of a cultivar in all the fields of a farm or of a specific region, and represents the state of the climate and soil and the ability of farmers to apply successfully the technology available to them.

The potential yield of a species in an area is achieved when the technology is not limiting, that is, when all inputs are used optimally. Strictly, this concept applies to the yield of a well fit cultivar with no limitations due to water or nutrients and full control of weeds, pests and diseases. In general, the potential yield is calculated using theoretical models based on climate and other environmental factors and on the morphological and physiological characteristics of the crop in question. In practice, these estimates of potential yield should be contrasted against record yields obtained by the best farmers in the same geographical area.

There is a considerable gap between actual and potential yield in most agricultural systems, so sometimes other indices are defined for diagnostic purposes For example, attainable yield is defined as the yield achieved within environmental constraints of climate and soil of the area, using the best technology available today. The yields obtained by the best farmers and research stations in the area are an indicator of attainable yield. The attainable yield in particularly favorable years, result in record yields.

The concepts of potential and actual yield (and to some extent attainable and record yields) are very useful for the evaluation of farming systems and the identification of possible improvements that will help in closing the gap between them. These concepts are also used to define cultivation intensity. In the intensive agriculture of Japan and Northern Europe, actual yields are close to potential yields and the yield gap is small. As yields approach potential levels, there is little incentive for farmers to further intensify production and there is always some gap between actual and potential production in all systems. As the difference between actual and potential yield increases, so do the opportunities to increase productivity.

1.4 Types of Agricultural Systems

Agricultural systems can be classified according to various criteria. An ecologically based approach is based on the type of trophic chain. The shorter chain is one in which crops are directly consumed by humans. In other chains, crops or pastures are eaten by livestock, which in turn is consumed by humans. The energy efficiency of a system is lower the greater the number of levels of the trophic chain. On average each transfer in a food chain has a net efficiency of about 10 %. Thus, for a net primary productivity of 100 units, if it is consumed directly (vegetarian diet), the transfer of energy is close to 100. If cattle are employed to transfer the energy to humans only 10 would be recovered. This does not imply that animal husbandry should be abandoned. On the one hand, animals are the only choice for exploiting marginal areas where crop production is not possible (see below). On the other, some animals can use materials not digestible by humans (e.g. cellulose in crop residues) or not suitable for food (e.g. food leftovers, residues from industrial processing).

Farming aims at minimizing energy flows through undesired routes (weeds, insects, etc.) that end up in the level of decomposers. As we have seen, a short food chain (crop → humans) is the most efficient from an energy transfer standpoint. However in many agricultural systems environmental conditions (for instance, very shallow/poor soils) prevent obtaining products for direct use by humans (e.g. grain production) and only pastures may be grown. There is also the case of areas with semi-permanent flooding or the very arid areas. In all of these situations, cattle allow the conversion of primary production to other usable forms by man, even at the cost of lower efficiency.

Agricultural systems may be characterized also according to their position within an interval that goes from subsistence agriculture to intensive agriculture. In subsistence farming, many species are used, cultivars are adapted to the specific environments, yield potential is low and actual yields are low but stable. They are also very labor-intensive and livestock is a main component in nutrient management. This leads to high energy efficiency. At the opposite extreme, intensive agriculture is characterized by lower genetic diversity (both in terms of species and cultivars) in search for high yields, greater use of machinery replacing labor, as well as high use of fertilizers and pesticides, resulting in high productivity but often with low efficiency.

Historically agriculture in developed countries has undergone a transition from subsistence farming to intensive agriculture with a continuous increase in productivity and a gradual decline in energy efficiency. The routes differ depending on how land use has evolved in the different countries: For instance, Canada, Australia and large parts of the USA and Argentina, have not intensified their agriculture as much as it has occurred in Northern and Central Europe and in Japan. In many Asian countries, a very intensive agriculture is practiced with high use of certain inputs and low yield gaps. Therefore in some developed countries we may find extensive systems with low inputs, but high level of mechanization, that require large areas for the farm to be economically viable, while in other countries (mostly developing) highly productive systems with high use of labor may coexist with subsistence agricultural systems.

The intensification of agriculture in many countries has led to major pollution episodes due to excesses in the use of inputs such as fertilizers and pesticides and, in some cases, to the production of agricultural surpluses due to ill-conceived subsidies. In some cases, food safety incidents have been related by the public opinion of these countries to agricultural intensification. This has led to proposals to develop alternative agricultural systems, some based on avoiding the use of mineral fertilizers and synthetic pesticides, such as in the different forms of biological or ecological agriculture, called organic farming. Other alternatives have proposed to adopt agricultural practices that are environmentally friendly and that ensure the quality and safety of food. The term "sustainable agriculture" refers to farming practices that allow the indefinite maintenance (sustainability) of agricultural systems, which requires the conservation of resources and the maintenance of economically viable farms. Some experts speak of a transition from traditional agriculture (low input, low control) to intensive agriculture (high input, low control), from which we must move to an agriculture which is more sustainable (inputs optimized, high control), where resources are used only in the appropriate amounts for each system and where there is a better control of the environment and the crop.

1.5 Decision Making in Agriculture

Farmers must combine a number of biological, physical and economic factors when making their decisions. The success of a farmer's activity can be measured by several variables (e.g. net income, yield, minimum risk, etc.), But not only is the average value of the variable important, also are its statistical distribution and extreme values. Agricultural activity is characterized by the uncertainty of a system that depends on the weather, which is highly variable and on relatively unpredictable biotic factors (pests and diseases). Therefore, the same agricultural practices can lead to different yields in different years. One can therefore assume that a set of agricultural practices will result in a frequency distribution of the variable considered (e.g. yield). Knowledge of this distribution would be necessary for the farmer to make decisions rationally. For example, a set of agricultural practices can result in a high average yield, but very low yields in certain years, which would have catastrophic effects on the economic viability of the farm. A farmer may choose to get a lower average yield in exchange for avoiding those years of very low yield.

Example 1.2 The result of two different nitrogen fertilization strategies (A = no fertilizer, B = 50 kg N/ha) over 30 years in a cereal crop is shown in Fig. 1.1. The average yield is higher for strategy B, but strategy A has a lower standard deviation (217 vs 583 kg ha^{-1}). Strategy B (apply fertilizer) implies a higher risk (lower yields in the worst years). If the farmer cannot stand a single year of low yield, strategy A will be preferred, although it involves lower average yield.

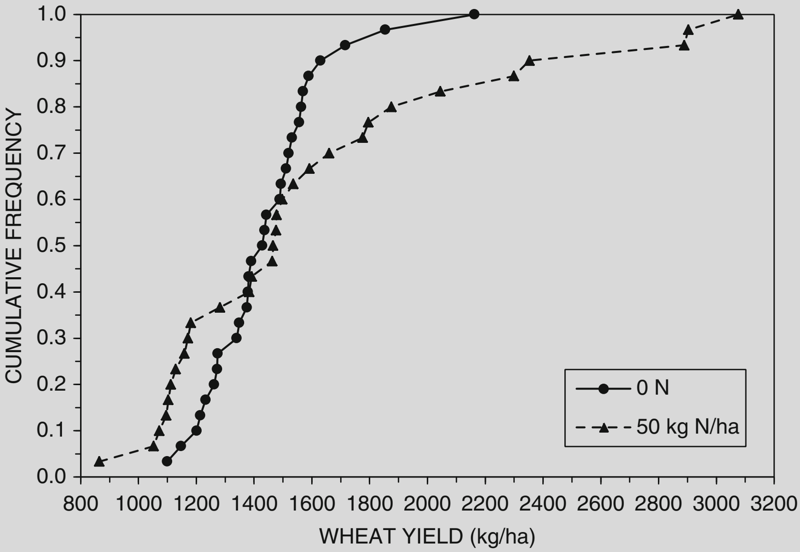

Fig. 1.1 Cumulative frequency of wheat yield with zero N fertilizer or 50 kg N/ha in a very dry area. The mean and standard deviations are 1447 and 217 kg/ha for zero N and 1606 and 583 for 50 kg N/ha, respectively

The uncertainty of farming is not just the result of climate variability and the possible occurrence of pests or diseases. Prices of agricultural products and inputs can deviate substantially from the expected prices for the farmer, which further hinders the process of decision making. The uncertainty of markets is proverbial, and more recently, the volatility of grain prices has caused food crises in several countries. The large price fluctuations have a very negative influence in the sustainability of farming, particularly in the case of fruits and vegetables, where there are many intermediaries between the producer and the consumer.

The general historical trend in agricultural systems around the world has been to develop management practices that reduce the risk, that is, to ensure sufficient yields in adverse years, but that do not fully exploit the potential in the most favorable years, even by sacrificing some yield in average years, thus not achieving the maximum average yield. In the past, when farmers did not have access to insurance or subsidies, a sequence of several years of bad harvests put in serious jeopardy the very existence of farming and the farmer. This has meant that avoiding risk is a priority in the strategic decisions of agriculture in many areas, particularly in rainfed systems. Examples would be the adoption of low tree density in rainfed olive orchards so that the tree always has enough water available, even in the worst droughty years, or the use of fallow in cereal rotations to store rainwater in the soil during the fallow year for the next crop. This tendency to avoid risk partly explains the slow adoption of new technologies in many agricultural systems, as compared to other productive sectors.

Decisions on a farm can be classified into four types (operational, tactical, strategic and structural) that correspond to different temporal scales. Operational decisions are made during the growing season (e.g. irrigation dates, amounts of fertilizer, date of application of an insecticide). Tactical decisions are made only once for each crop (crop choice and sowing date, target yield, etc.). Strategic and structural decisions have an impact on a number of crops (e.g. farm production orientation, investment in machinery, infrastructure improvements). Obviously, if we deal with multiannual crops (e.g. orchards), the temporary classification is changed, as in this case, the tactical decision affects a number of crop seasons.

1.6 Sources of Information for Decision Making in Agriculture

The farmer needs to know how the crop responds to different agricultural practices in a particular environment (soil and climate). Also, in order to make operational decisions, information is needed on the status of the crop and of the soil throughout the season. The sources of information available to the farmer to make decisions are quite diverse in terms of quality of information and of the cost associated with its acquisition. Today we tend to consider information as a production factor, absolutely necessary for efficient agriculture. The different sources of information available on how crops respond to different management practices are discussed below, with the exception of new technologies and the concept of Site Specific or Precision Agriculture which are presented in Chap. 33.

1.6.1 Farmer's Experience

The experience of the farmer is the traditional way on which all agricultural activity is based, and it may be the best source of information on agricultural systems that vary little over time. Local knowledge has developed over many generations and it integrates the multiple features of the environment and the society as they affect agriculture. It represents the human capital of a rural area which needs to be protected and preserved. While traditional knowledge is always useful, sometimes it presents difficulties for adopting innovations or to adapt to new situations (crop or variety changes, new technologies, appearance of new pests and diseases, etc.).

The complexity of the agricultural system in which many biotic and abiotic factors interact, makes it difficult to correctly interpret the observed responses and to achieve a good understanding of system performance based solely on experience. Often, a particular phenomenon may be due to causes that have nothing to do with the apparent causes.

An additional problem is the adoption of farming practices, based on the "collective experience", which may be detrimental in the long term, even if they do not cause any apparent injury, thus remaining unchanged over time. As an example, we can cite the excessive tillage used for decades in many agricultural systems. Finally, another drawback of using only experience as the basis for decision making is the difficulty to detect processes that damage natural resources over the long term. A classic example is the loss of soil by water erosion, difficult to detect except when torrential rains create gullies that are obvious. However, corrective measures, once gullies occur, are no longer effective. Other problems such as salinization or acidification are very difficult to detect just by experience until the problem is severe and difficult to overcome.

1.6.2 Research, Experimentation and Technology Transfer

Research leads to new knowledge, new processes or new products. Research and experimentation are the only ways to produce new knowledge about the management of agricultural systems. There has been great emphasis in many developed countries for significant investment in agricultural research since the mid-nineteenth century. It can be said that these investments were the engine of economic development in these countries until the early decades of the twentieth century. Subsequently, investments in agricultural research have been the basis on which they have founded the notable increases in agricultural productivity since 1950, to the point that all the impact studies show that these investments stand as one of the best business of the public sector of all times. The success of agricultural research in the developed countries led to the creation around 1960 of a network of international agricultural research centers located in developing countries such as Mexico, the Philippines, India, Nigeria, etc. These centers are managed and coordinated through the Consultative Group on International Agricultural Research, which brings together more than 50 countries and international organizations and have been responsible for the worldwide development and dissemination of new varieties for the major crops, and for the introduction of management techniques to intensify production in a more sustainable fashion.

For scientific knowledge to reach the farmer and to adapt it to its needs, institutions were needed to transfer the new knowledge in parallel to those dedicated to research. These institutions are called agricultural extension services. The prestige and usefulness of extension services have been highly variable in the different countries, according to the investment, its tradition and the various forms of organization adopted. The growing use of the Internet as a source of information and of technology transfer has also taken place in agricultural extension. Extension services of U.S. universities often maintain pages with plenty of information for farmers in different states. An example is the page about horticulture at the University of California at Davis (http://virc.ucdavis.edu).

Agricultural research is often based on field experiments, usually performed in experiment stations, which are farms devoted to research and technology transfer. Results of experimentation have a limited validity in agriculture. As said before, a set of agricultural practices could have different results in different years. The same applies to the results of one experiment. Thus agricultural experimentation is slow and expensive (needs to be replicated for a number of years). Adopting the experimental results of a single year can lead to significant errors. It is necessary, therefore, to consider the results of several years and yet, there is uncertainty in extrapolating the results to other environments. This limitation highlights the need to use other tools to complement experimentation in decision-making.

1.6.3 Commercial Information

Many of the inputs needed in farming are commercialized and the private sector has made significant investments in research, particularly in recent years, and is very active in technology transfer in the agricultural sector. For products and services offered by the private sector, technology transfer is very effective. However, there are issues of agricultural production systems, for example in the area of natural resources management, where there are many stakeholders and where societal interests may not always compatible with the interests of the private sector. Furthermore, there are no economic incentives for the private sector to generate all the information that is required for the sustainable management of natural resources. While commercial information can be very useful for the farmer, often it is promoted in such a way that tends to overestimate the benefits of the products. Examples include the indiscriminate use of foliar fertilization and of some soil amendments.

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