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Weed ↔ Crop Competition

A review

Weed-Crop Competition
A review

by R. L. Zimdahl

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Preface

Impetus for this review stemmed from my opinion that many weed scientists in developing countries do not receive current literature regularly and have even less access to many journals commonly found in libraries of the developed world. Thus they are denied use of printed resources that help develop an historical perspective. A broad view, when combined with the stimulation of current research, sharpens the focus of research programs and facilitates their justification to administrators and funding agencies. Lack of access to the literature can narrow one's perspective and severely impede development of weed research programs.

The realization that no comprehensive review of weed-crop competition had been published and that the International Plant Protection Center at Oregon State University was willing to fund such a project generated additional motivation.

The review, in the main, constitutes a report of what has been done by whom. It includes articles directly related to weed-crop competition published prior to June 1978.

Authors resist uniformity and use a variety of notations and measurement systems. The current convention of using only metric units was tempting. However, readers who elected to consult a particular paper would need to convert back to the original units. Therefore, the units from the original paper were used without conversion. A conversion table has been included.

All weeds are cited by scientific name used by the author; equivalent scientific (where required) and common names accepted by the Weed Science Society of America are included in Index Table B. The scientific name of each crop is included at first mention, but thereafter reference is by common name. Equivalent names are in Index Table A.

Most papers selected for inclusion specifically discuss weed-crop competition. Others provide background or fundamental information. Most literature concerning crop-crop interactions has been omitted as has that dealing with environmental conditions that stress crops (e.g. low water, high

temperature) and increase their susceptibility to weed competition.

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Fort Collins, Colorado / USA
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I.

Introduction

Two of the earliest known references concerning effects of weed competition appear in ancient religious writings (Bible, Genesis III:17-18): "Cursed is the ground for thy sake; in sorrow shalt thou eat of it all the days of thy life; thorns and thistles shall it bring forth to thee; and thou shalt eat the herb of the field." Another passage (Parable of the Sower, Matthew XIII:7) notes that, "some fell among thorns; and the thorns sprang up, and choked them." Certainly competition between plants precedes recorded history and was recognized long before a defined term was assigned to it.

Competition is the predictable response of grouping living organisms into communities. Clements et al. (140) provided an early history of the literature. Competition was recognized and reported by Petrus de Crescentiis in 1305 in a forest community when he directed that trees be cut first where they were too thick. Malthus, in 1798, stated, "The cause to which I allude is the constant tendency in all animated life to increase beyond the nourishment prepared for it."

In 1820 Decandolle described plant competition when he stated that all species of a region and all plants of a given place are in a state of war with respect to each other. He derived a theory of antagonism between phanerogams (1832), and a theory of crop rotation based on the idea that succeeding species should be those not inhibited by toxic substances left by preceding crops. One of the first studies of plant competition was completed when Sachs attempted to relate soil mass to yield in 1860. Nageli in 1865 broadened the significance of competition in the plant community, pointing out that it furnished a solution to the problems centering on the presence of lime in the soil.

Darwin (147) derived the concept of competition in nature as a whole and considered it almost ubiquitous and omnipresent. In reviewing Darwin's exposition of competition in the *Origin of the Species*, one can easily overlook the fact that he regarded competition as only one component of the struggle for existence, but possibly the most important one.

Nageli (cited in 140) sought to give mathematical form to the suppression of plants by their competitors. He concluded that

respective numbers were determined by the average life period and the average annual growth increment. In 1895 Macmillan (cited in 140) considered competition between species and the struggle between communities. He was one of the first to express the view that there are certain points of resemblance in the competition for food which takes place between similar individuals and causes the weaker to be more or less suppressed. Clements et al. (140) stated that, "Competition is a question of the reaction of the plant upon the physical factors that encompass it and of the effect of these modified factors upon adjacent plants."

Haldane (218) noted, "The fitness of plants in the Darwinian sense must be tested with the plants grown in competition." Thus, any complete analysis of plant competition must involve plants in a community and their communal relations, plus individual plant growth patterns and the growth of individual plants in isolation.

Brenchley (77), in conducting studies of various weeds with cultivated crops, observed that some weeds were generally found in association with certain crops and others were common among all cultivated crops. She hypothesized that one of the foremost factors determining a particular weed species' abundance or scarcity was its ability to withstand competition. The above ground struggle for light, she stated, was as important as the underground competition for nutrients and moisture. These three primary elements of plant competition—light, nutrients, and water—are repeatedly mentioned in the literature. Major sections of this review will focus on each. □

II.

Definition of Plant Competition

"Where there is so much of competition and uncertainty you must expect self interest will govern."

*Jeremy Collier, 1697
"Essays on Moral Subjects"*

The 1933 edition of the Oxford English Dictionary (384) defines competition as, "the action of endeavoring to gain what another endeavors to gain at the same time; the striving of two or more for the same object—rivalry." Despite this concise definition, the exact meaning of the term competition is confused in the literature. Milne (344) proposed that confusion resulted from: (1) a misunderstanding of Darwin's original usage; (2) neglect of the etymology of the word; and (3) the mixing of competition with results. Milne, who worked with animals, found wide disagreement among definitions.

Bunting (100) thought competition had different shades of meaning for the agronomist and the plant physiologist. Physiologists may think of competition as being for something, usually nutrients, water, or light. Agronomists, while agreeing, may add that competition also exists between plants or parts of the same plant. Thus, many definitions have been proposed and these were reviewed by Milne (344).

1. Mather (329): "Competition implies the presence of one individual as an effective part of the other's environment and a similarity of need or activities so their impact on each other is prospectively detrimental."
2. Aspinall and Milthorpe (35): "The interaction between plants and environment. Plants during growth modify the environment around them and the modified environment in turn influences the growth of the constituent plants."
3. Bleasdale (68): "Two plants are in competition with each other when the growth of either one or both of them is reduced or their

form modified as compared with their growth or form in isolation."

4. Milne (344): "Competition is the endeavor of two (or more) animals to gain the measure each wants from the supply of a thing when that supply is not sufficient for both (or all)."
5. Birch (55): "Competition occurs when a number of animals (of the same or of different species) utilize common resources the supply of which is short; or if the resources are not in short supply, competition occurs when the animals seeking that resource nevertheless harm one or the other in the process."

Harper (227, 228) decided that many definitions proved excessively cumbersome and, in his work, adopted the inclusive term, interference, which had been suggested earlier by Muller (358). The term includes competition and allelopathy. Allelopathy has been specifically excluded from this review. For information the reader is referred to the book, *Allelopathy*, by E. L. Rice (420). Allelopathy is distinguished from competition because it depends on a chemical compound being added to the environment while competition involves the removal or reduction of an essential factor from the environment.

The confusing pattern of definitions notwithstanding, workers concerned with plant competition discover, with pleasure, the two major points of plant competition outlined by Clements et al. (140) followed by an inclusive definition. The principles are, first: "Competition is keenest when individuals are most similar and make the same demands on the habitat and adjust themselves less readily to their mutual interactions." Second: "The closeness of competition between plants of different species varies directly with their likeness in vegetation or habitat form." Dissimilarity tends to eliminate competition and preserve the advantage of the superior form.

The two principles precede the following definition of plant competition: "Competition is a purely physical process. With few exceptions, such as the crowding of tuberous plants when grown too closely, an actual struggle between competing plants never occurs. Competition arises from the reaction of one plant upon the physical factors about it and the effect of the modified factors upon its competitors. In the exact sense, two plants, no matter how close, do not compete with each other so long as the water content, the nutrient material, the light, and the heat are in excess of the needs of both. When the immediate supply of a single necessary factor falls below the combined demands of the plants, competition begins."

Donald (171) combined the definitions of Milne for the animal world and Clements for plants into a concise statement: "Competi-

tion occurs when each of two or more organisms seeks the measure it wants of any particular factor or thing and when the immediate supply of the factor or thing is below the combined demand of the organisms."

One often reads of competition for space, and while this may be an actuality in the animal kingdom, it is not usually the case with plants. Rivalry for space may occur with *Beta vulgaris* L. (sugar-beet) or *Daucus carota* L. var *sativa* D.C. (carrot) when two roots actually touch or become intertwined. Generally, the phrase implies competition for the elements space contains—nutrients, water, or light—rather than space itself.

Another point: the association of two or more plant species does not always result in competition. A prime example exists in the symbiotic association of legumes and grasses. Mather (329) discussed this aspect of plant relationships. Donald (171) provided another example, the germinating seeds of *Trifolium subterraneum* L. (subterranean clover). The dormancy found in some varieties of this species for many weeks after harvesting may be broken by exposure to an atmosphere containing 0.5% carbon dioxide. If one seed in a dormant group germinates in a normal atmosphere it will provide enough carbon dioxide to initiate germination of the rest.

Donald (171) also mentioned that competition cannot be assumed to occur simply because a factor is in short supply. If all plants in a community are exposed to insufficiency while the environment of each is independent of its neighbors, there can be no competition. He used the example of poor oxygen supply delaying germination and growth of *Triticum aestivum* L. (wheat) seedlings in overwet, poorly structured soils. However, the circumstance is exceptional and competition soon occurs.

Plants cannot be considered to compete for heat because heat is not present in finite amounts. Competition for carbon dioxide may occur, but probably only under extremely crowded conditions. Most of the factors for which there is competition are found as a pool from which supplies are drawn, according to Donald (171). This concept can be easily visualized for water and nutrients but not for light. Light must be intercepted when available or lost forever. Thus, foliar height and breadth will determine a plant's effectiveness as a competitor for light. Referring again to Clements et al. (140) to further elucidate the concept of a pool and its usage: "It is evident that practically all the advantages or weapons of competing species are epitomized in two words—amount and rate. Greater storage in seed or rootstock, more rapid and complete germination, earlier start, more rapid growth of roots and shoots, taller and more branching stems, deeper and more spreading roots,

more tillers, larger leaves and more numerous flowers are all of the essence of success." Thus, nothing succeeds like success.

Competitive ability has been proposed as a genetic character controlled by polygenes, but not associated with morphological characters such as height, growing habit, and vigor of growth (442). The heritability of the trait is very low and the outcome of competition may vary not only with intensity, but with the environment of its occurrence. □

III.

Competition in the Community

Monoculture rarely occurs in natural environments which favor communal life for plants. Nature does not recognize the human categories of domesticated plant, or the inalienable rights of man. In natural environments living organisms are engaged in relentless competition with peers as well as with many other organisms. Plants do not escape the struggle for existence. Brenchley (76) emphasized the omnipresence of competition as a vital factor in the plant community when she said that, "It is impossible to sow a crop without the certainty that other plants will appear."

Pavlychenko and Harrington (396) have shown that competition exerts a powerful natural force in the plant community tending toward limitation or extinction of weaker competitors. They found that, within the community, each weed and each plant differed greatly in competitive ability and that all weeds suffered greatly from competition with crop plants.

Donald (171) began a discussion of density in the community with an examination of the relationship of density to total yield of dry matter, the biological yield of various crops. He pointed out that studies to determine optimum sowing rate rarely include a sufficiently wide range of densities to permit definition of the relationship of density and yield. The data from Donald's experiment on intraspecific competition among annual pasture plants (167) indicate the relation of yield of dry matter to density at zero days (weight of seed embryo), 131 days and 181 days in subterranean clover grown with adequate moisture and nutrients. At planting, there was a linear relation between density and yield. Competition for light developed in dense populations soon after germination and thereafter became operative in populations of lower and lower density. Competitive effects stopped growth at highest densities. Because of extreme growth rate reduction late in the season and concurrent high growth rate in sparse stands, the latter tended to approach the more dense stand in final yield. The final data showed that yield of dry matter is constant from moderate to high densities. The original linear relationship of density to yield of dry matter was replaced by a curve in which yield rose

sharply with increasing density to a maximum which was constant for all higher densities.

This work also stresses that the determination of optimum density for an early harvest is more difficult than at maturity. For an early harvest, the greater the density the greater the yield because the earlier harvest will come at a time when interplant competition is less intense with consequent lower yield depression.

The work of Aspinall and Milthorpe (35) presents a similar relationship by analyzing competition between *Hordeum vulgare* L. (barley) and *Polygonum lapathifolium* where a constancy of final yield of dry matter per unit area at moderate to high densities has been measured.

Mann and Barnes (321, 322, 323, 324, 325), in several carefully conducted competition experiments, provide further examples. In their first experiment (321) yield of crop and weeds tended to reach a maximum with a definite density of plants per volume of soil. However, effects between plants were inconsistent. *Spergula arvensis* and *Matricaria inordora* limited the growth of barley and were in turn limited by barley. The same held true for *Trifolium* spp. (clover) (325) and the grass *Agrostis gigantea* (323), in competition with barley. The effect of *Holcus mollis* (322) depended upon which became established first in the community and barley seeding rate. The weed established the previous year and a thin stand of barley could reduce barley yield up to 100%. Competition of barley with *Stellaria media* varied slightly in that the weed reduced the yield of barley, but the opposite relation was not true primarily because of more rapid development of *S. media* roots (324).

A comment by Salisbury (443) summarizes, "Below a certain specific density the increased yield of the individual fails to compensate for the diminished population. On the other hand, above a certain density the individual becomes so depauperate through competition, that the augmented population fails to compensate for the low yield of the individuals." Although Salisbury was speaking of the individual in a monoculture, his reasoning can be extrapolated to the community.

The literature on competition generates the question of determining if a given unit of soil will produce a fixed increment of growth and yield with the prevailing environment, or if the competitive influence in annual crops intervenes. The experiment by Aspinall and Milthorpe (35) has been cited in this regard. Robinson and Dunham (430) found that *Glycine max* L. (soybean) produced normal yields, and sometimes more, when forage companion crops were interseeded with soybean rows. As *Zea mays* L. (corn) was intercropped with *Phaseolus aureus* Roxb. (mung bean) and the

level of weed control reduced, the relative advantage of intercropping increased so its productivity was 75% greater than a monoculture (39). The response of weeds was correlated with light interception ability.

Mann and Barnes (321) showed that with a constant amount of weediness from either of two weeds, an increasing density of barley plants diminished the injurious effects of the weeds. The combined weight of barley and weeds was rarely as great as barley alone in a weed-free plot. The research team stated that with a constant density of barley and a variable density of weeds, the total weight of the above-ground portion of barley and weeds was almost constant whatever the number of weed plants of either species.

Moolani and Slife (353) found that dry weight of weeds and corn combined was equal to the weight of weed-free corn. However, with soybeans the crop plus weeds equalled one and one-half times the yield of weed-free crop. In another experiment with corn and soybeans, Knake and Slife (296) found that increases in dry matter of *Setaria faberii* were proportional to decreases in dry matter from the crop. The combined yield did not vary significantly. Similar results were reported by Shadbolt and Holm (458) working with vegetables.

Staniforth often mentions total yields in his work with soybeans, but the results are inconsistent. In two experiments (480, 490), yield of soybeans alone was almost equal to soybeans plus weeds. In other work (551) yield of soybeans and weeds was slightly higher than when soybeans were grown alone.

No definite answers to this question have been provided from work with root crops such as sugarbeets.

Allison et al. (18) present a possible explanation and avenue toward further research. In a discussion of the relationship between evapotranspiration losses and yield, they found a direct and high degree of correlation between evapotranspiration and the dry weight produced by above-ground parts. This was true regardless of crop rotation or fertility level.

The weight of evidence, to be presented herein, is such that no generalizations can be made concerning constancy of community yield. Specific conclusions can only be reached with reference to species and environment which, of course, vary for all experiments. Natural environments favor community life for plants. Thus, a question arises concerning the possible interactions when two or more species are grown together. While pasture and hay crops are usually seeded as mixtures, most western agriculture relies on monoculture. The question of advantages for mixed cultures persists.

Donald (171) observed that native pasture communities commonly develop great complexity with several layers of each species. He asked, "Can such a community structure exploit the environment to a maximum?" If light-tolerant species will grow beneath the canopy and if roots with varying degrees of dispersement and penetration will better exploit available moisture and nutrients, the answer may be yes. Plants integrate all the variables in any environment, justifying the use of dry weight as an ultimate index of competition (68). Therefore, the final question becomes: can two species fix more carbon dioxide when growing in association than either species growing alone?

Clements et al. (140) described competition for two factors. "The beginning of competition is due to reaction, when the plants are so spaced that the reaction of one affects the response of the other by limiting it. The initial advantage thus gained is increased by cumulation, since even a slight increase in the amount of energy, as raw material, is followed by corresponding growth, and this by further gain in response and reaction. A larger, deeper or more active root system enables one plant to secure a larger amount of the chresard (available water:) and the immediate reaction is to reduce the amount obtainable by the other. The stem and leaves of the former grow in size and number, and thus require more water; the roots respond by augmenting the absorbing surface to supply the demand and automatically reduce the water content still further. At the same time, the correlated growth of stems and leaves is producing a reaction on light by absorption, leaving less energy available for the leaves of the competitor beneath it, while increasing the amount of food for the further growth of absorbing roots, taller stems, and overshadowing leaves."

Clements' view strongly suggests that for two associated species, one will be suppressed while the other will dominate. Ahlgren and Aamodt (5), in contradiction, suggested that when some common mesophytic plants are grown in pairs the yield per plant of both species in the mixture may be less than the yield per plant in each of the corresponding pure cultures. They tested their hypothesis with *Agrostis alba* and *Poa pratensis*, obtaining supporting, but statistically insignificant, data. They also worked with *Phleum pratense* and *A. alba* and developed significant results. (They were observing allelopathy, as suggested by their title. The recent text by Rice (420) presents a complete discussion of allelopathy.)

An examination of several experiments (1, 171, 187, 427) with forage or grass species reveals extensive support for Donald's (171) analysis of possible results when two species grow together. In summary:

- (1) the yield of the mixture will usually be less than that of the higher-yielding pure culture;
- (2) the yield of the mixture will usually be greater than that of the lower-yielding pure culture;
- (3) the yield of the mixture may be greater or less than the mean yield of the two pure cultures;
- (4) there is no substantial evidence that two species can exploit the environment better than one.

In another study Donald (169) indicated that competition for two factors leads to multiple interactions between two groups of effects and thus greatly intensifies the effects of either factor operating alone. Aggressor species showed a negative interaction between the effect of two modes of competition, i.e. light and nutrient, or light and water. Yields dropped slightly due to competition for either factor alone, but when competition for both factors operated, yields approached levels obtained in the absence of competition. The aggressor competed more effectively when both means of competition were available to it. The effect of the two modes of competition on the suppressed species showed a positive interaction. Yield depression, under competition for both factors, greatly exceeded the sum of the effects of competition for the separate factors.

Studies of competition between associated species, other than forage crops, are rare, and perhaps justifiably so because other crops are rarely grown in the same manner. Hanson et al. (226) and Hinson and Hanson (253) found that the advantage gained by one of a competing pair of soybean genotypes equaled the loss sustained by the other. They considered competition between soybean genotypes to be additive.

Stringfield (498) observed that when two corn hybrids were grown in association, no marked advantage or disadvantage in productivity accrued to the mixture compared with the average of the contributing hybrids when grown separately. The results held constant whether the members of a given hybrid pair were alike or widely different. Again, increase in yield by one balanced decrease in yield of the other.

Two corn genotypes with widely different heights were grown in association by Pendleton and Seif (401). Alternate rows of US-13, 106 inches tall, and a brachytic 2—dwarf version of US-13, 72 inches tall, were planted. In direct contrast to Stringfield's (498) results, the mixture yielded 7 bu/A less than the mean of the two pure cultures. The authors pointed out that considerable shading of the dwarf by the taller corn occurred, but very ineffectual shading of the lower leaves of the taller by the dwarf.

Overall, the limited data available indicate relatively little gain from mixing species, but other advantages obtainable in certain environments, economic situations, or crop rotations should not be dismissed. Harper and Gajic (230) emphasized that knowledge of factors controlling population in the plant community also determines the extent of understanding reasons for one species succeeding at the expense of another. The same information helps explain why a diversity of plant species may cohabit a relatively stable community without one succeeding at another's expense. The principle offered by Gause in 1934 (203) seems to contradict this; two species, he said, scarcely ever occupy similar niches, but displace each other so each takes possession of certain resources which give it a competitive advantage. The view has been labeled the competitive exclusion principle. Experiments with *Drosophila* show that two species can compete for limited resources and still co-exist (37). The process of natural selection leads toward ecological differentiation of competing species and therefore promotes stability of ecosystems even though competition is an unavoidable consequence of communities.

Changes or shifts over time of the weedy species present in a disturbed (cropped) community are a secondary effect of weed management by any means. Intensive cropping systems give rise to weed communities that are products of cropping patterns and weed management systems rather than just a result of "natural" competition and succession (232). The fact that weed-crop competition takes place in such disturbed communities demands special techniques for study and analysis of results. □

IV.

Influence of Competition on the Plant

Competitive ability relates to a polygene controlled genetic characteristic, whose action is influenced by environmental interactions (442). Competitive ability can be measured using vegetative growth rate or propagation rate, terms which are usually consistent with each other. However, to be most accurate, plant character variation due to competition must be observed as it is affected by intergenotypic competition (441). The environment varies in physical characteristics to which plants respond; plants compete for some of these (water, nutrients, light), but not for others (e.g., time of planting, time of emergence) (438). The presence of neighbors of the same or different species may alter the environment to such a degree that a species that is unable to gain an early advantage also may be unable to exploit a competitive advantage later (438). For example, a high relative growth rate late in the growing season becomes valueless if a competitor has consumed the bulk of available soil nutrients. To truly understand the individual in the population, experimental designs must recognize and include the reaction of individuals to the presence of others.

Harper and Gajic (230), studying the response of *Agrostemma githago* to increasing density, theorized that plants could respond in two ways: 1) by increased mortality, and 2) by increased plasticity in size and individual reproductive capacity. In either way an individual annual plant can react to increasing density and, thereby its population becomes self regulatory. Harper (229) argued that the essential properties controlling the ecology of a species only can be detected by studying it in competition, and that its behavior in isolation may be irrelevant to understanding behavior in the community. Thus, comments in this section must always be related to those in the previous section. For example, in a study of weed competition with corn and soybeans, Moolani et al. (352) found the heaviest stands of *Amaranthus hybridus* reduced corn yield an average of 55%. There are many similar studies (only a few are cited) which cite varying yield reductions from competition

between crops or between crops and weeds (80, 85, 87, 109, 117, 108, 119, 120, 122, 150, 162, 171, 200, 321, 322, 323, 324, 341, 352, 377, 459, 471, 474, 483, 486, 503, 537).

Weber and Staniforth (551) stated that differences in the competitive efficiency of crops and weeds are well known. The above citations support their statement and provide experiment results. However, only clues and patches of evidence surface relating to why such things occur. While knowing that stands of *A. hybridus* reduce crop yields a certain percentage is useful, the larger question of why this is true and why the effect should vary with crops poses a more interesting challenge to research workers in the field of plant competition.

Clements et al. (140) described plants' competitive equipment and provided valuable information on interplant competition. The authors cited four points, all centering on the determination of life form:

- (1) Duration or perennation—owing its effect to occupation and height;
- (2) Rate of growth—most effectively expressed by expansion and density of the shoot and root systems;
- (3) Rate and amount of germination—initial advantage;
- (4) Vigor and hardiness—facilitate survival under stress.

Hodgson and Blackman (254), in a detailed analysis of the density response of *Phaseolus vulgaris* L. (field bean), concluded that a profound difference often occurs in the way plants with determinant and indeterminant growth respond to density. Species such as field bean, in which the flowering apices do not arise from the major vegetative apices, mainly respond to density by altering the number of parts formed. In contrast, *Helianthus annuus* L. (sunflower) and similar species respond more by changes in the size of parts. Blackman (64) in a 1919 study of the compound interest law and plant growth stated that, "In many crop plants the matter (of plant growth) is of course complicated by the effect of crowding on the individual plant."

What are the complicating competitive factors inherent in the study of plant growth? One of the more substantive recent explanations of the sum of the factors encountered by an individual plant has been schematically outlined by Bleasdale (68). He proposed that competition encountered by an individual plant depends on the density, distribution, duration, and species of its competitors (Figure 1). Climatic and edaphic conditions serve as modifiers.

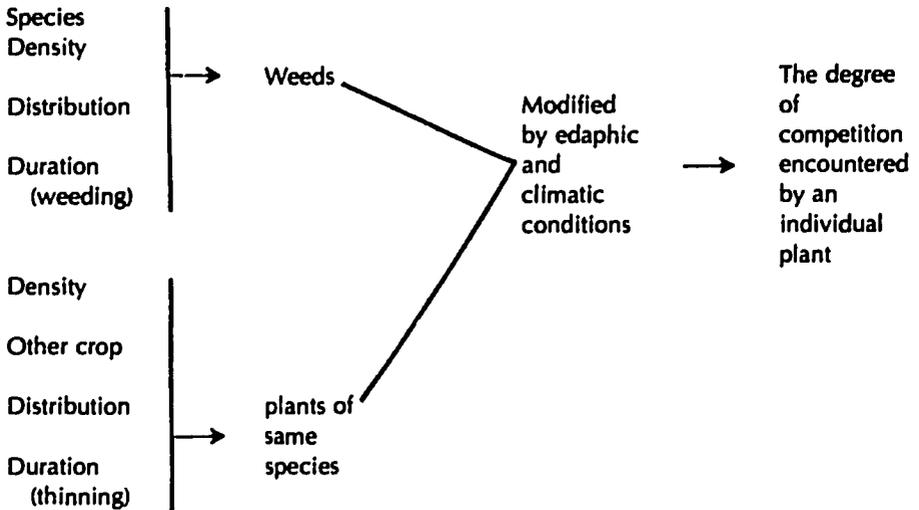


FIGURE I

Schematic diagram (after Bleasdale [68]) depicting the competition encountered by an individual plant.

Palmblad (387, 388) considered several factors on the left of Bleasdale's scheme in an investigation of seven weeds. Friesen (199, also cited in 438) posed a series of questions focusing on the heart of weed-crop competition and enumerating the as yet unknown interactions suggested by Bleasdale.

- What densities are necessary to reduce yields?
- Do similar densities have similar effects in all crops?
- At what stages of development does competition occur?
- What is the influence of fertility and moisture?
- How far (great) is a delay in sowing (or emergence) of the crop important in determining the outcome of competition?
- How reproducible are the effects of weeds from field to field, area to area, and country to country?

To this list of questions can be added:

- How do different species (or populations) of weeds compare? (438)

Donald (171) stated that plants show extreme plasticity, responding remarkably in size and form to environmental conditions. He emphasized that the presence of a neighbor (plant) constitutes one of the most potent external forces that may limit size and ultimate yield. Harper (229) stated that, "The form,

tolerances, and persistence of species may be profoundly modified by the proximity of neighbours (sic) of the same or other species. It follows that the characteristics of individual species shown by isolated individuals or pure populations may offer no significant guidance to their behavior in the presence of others."

Characteristics leading to competitive success only can be exposed and demonstrated when species grow together. The concept of plant plasticity in response to competitive environment was advanced by Harper (227). Because of plasticity, reducing seeding rates by half may not affect crop yield when remaining plants more nearly approach their biological potential (227, 387). Donald (171) said, "It is a surprising thought that man, in growing a successful, healthy field crop creates such intense competition that the individual plants are, in a very real sense, subnormal." He obtained maximum levels of dry matter production per pasture plant at lowest densities and a decreasing trend with increasing density (168). Seeds per inflorescence and the weight per seed actually rose to a peak at intermediate densities, and then fell.

Donald's reasoning for these results centers on inter- and intraplant competition. At the least dense planting, competition was absent during early growth stages when flower primordia originate. As growth proceeded, interplant competition became progressively stronger. At flowering and seed formation, the total number of inflorescences was so great competition occurred among them. Seed production efficiency decreased leading to fewer seeds per inflorescence and reduced seed size, at the widest spacing. Therefore, at lesser densities intraplant competition prevails. In extremely dense stands, competition is already intense at the time primordia originate and both intra- and interplant competition function continually. However, in a moderately dense stand, interplant competition operates at the time of floral primordia initiation reducing the number of floral primordia formed. This reduced number more nearly matches the plant's capacity as interplant competition intensifies, while seeds per inflorescence and per unit area achieve a maximum. Thus, competition within plants and between plants combine to produce maximum seed yield per plant. Donald suggested that, at least density, competition within the plant may be the governing factor resulting in maximum yield (of any plant component).

However, Harper and Gajic (230) indicated variability in seed set was greatest with *Agrostemma githago* (1 to 24 capsules/plant) at low densities and least (almost all plants with a single capsule) at high densities. This work suggests that variation is greatest at lower densities in contrast to the Donald's findings (above) and other work reported by him (171).

Roots as vital, functional plant parts influence competitive relations although less experimentation has been conducted. Clements (139) mentioned that slight competition occurs between aerial parts of grasses with erect leaves; as a result, competitive interactions chiefly center in the root zone. Mann and Barnes (321) thought that with nitrogen fertilizer in excess of the amount needed by the crop, any yield reduction of barley "must" be due to competition for root "space." All possible variables, with the exception of light, were reportedly more than optimum in the experiment. However, *Spergula arvensis* and *Matricaria inodora* are shorter than barley; hence, light could have been limiting.

Pavlychenko and Harrington (396, 397) discussed weeds' competitive efficiency in cereal crops and proposed that: root system development may be more important than early germination or the development of a large assimilation surface; root systems nearest the surface were most effective in competition. They found most weeds (20 days after emergence) had larger root systems and greater assimilation surfaces than any of the common cereals tested (397). In other work, specifically on root development as related to competition, they noted that the capacity of the root system developed by competitors influenced competition between some cereal grains and weeds (396). The research was conducted on the Western Canadian plains where moisture is commonly the limiting external factor. Root system capacity immediately after germination and emergence was especially important.

Pavlychenko (394), in a detailed examination of the root systems of weeds and crop plants, presented a picture of the competitive relations of roots. He traced total root development and carefully measured final development. For several days after actual germination and before emergence, plants develop in darkness with no photosynthetic organs. The roots are the main functional exterior organs during this period. The size of the plant increases 3 to 400% prior to emergence primarily due to root development. Competition, which begins as soon as roots attempt to occupy the same space, may occur early in development and affect development of above-ground parts. Pavlychenko found extensive root competition to be the rule. Single mature plants grown in the center of 10-foot squares produced total root lengths of:

Avena fatua: 3,456,005 inches

Triticum aestivum L. (wheat): 2,802,821 inches

Secale cereale L. (rye): 3,114,375 inches

When the same plants were grown in 6-inch rows with 18 to 20 plants/ft, a different ratio was obtained and root system lengths decreased 83 to 99 times.

Pavlychenko also grew cereal crops in 6-inch drill rows with weeds between the rows and compared crop root systems 40 days after emergence:

<u>Type of competition</u>	<u>Ratio of root system length</u>
Barley— <i>A. fatua</i>	7.7 : 1.4
Barley— <i>Brassica kaber</i>	6.2 : 2.4
Wheat— <i>Brassica kaber</i>	3.3 : 6.5

Similar effects were noted in competing aerial plant parts.

Black et al. attempted to provide a biochemical basis for plant competition (56). They examined data from many other studies and placed plants in an efficient or non-efficient group based on six criteria. From this grouping the researchers proposed an hypothesis to explain the competitive success of several crop and weed species. The criteria were:

1. response to light intensity;
2. response to increasing temperature;
3. response to atmospheric oxygen;
4. presence of photorespiration;
5. level of photosynthetic carbon dioxide compensation concentration;
6. pathway of photosynthetic carbon dioxide assimilation (C_3 vs. C_4 CO₂ fixation cycle).

After classifying over 50 crops and weeds the team concluded that competition among plants depends on morphology, differential response to environmental parameters, ability to extract nutrients and water from soil, and other factors. However, they proposed that competitive ability also depends on, and partially can be explained by, the net capacity of a plant to assimilate carbon dioxide and use the photosynthate, an ability intimately linked to the six criteria. Plants that fix carbon dioxide at high rates probably secure an initial competitive advantage and develop into high yielding crops or vigorous weeds. The research group's analysis supports this conclusion. A second paper (135) affirmed the validity of their original hypothesis through an examination of carbon dioxide compensation concentration, photosynthetic rate, and carbonic anhydrase activity. Low carbonic anhydrase activity normally accompanies a low compensation concentration.

Some of the numerous factors affecting individual plants have been mentioned or generalized (see Bleasdale 68). The review's focus now shifts to more fully describing major elements of competition between individual plants.

Although his statement is nearly 30 years old, Donald (171) wrote an excellent and still currently valid appraisal of man's understanding of competition among plants.*

"It is a salutary thought that we do not know—nor have we even given the matter much consideration—what determines the density of population of cereal plants giving maximum yield. Yet until we know this, and especially until we understand the interaction of density with such factors as water and nitrogen, then the development of suitable varieties of plants must depend in the future—as in the past—on empirical plant breeding. We can claim great advances in genetics, and great advances in producing plants with drought escape or disease resistance, fatter pods or finer flowers. And the breeder can point, too, to varieties which, quite apart from these specific virtues, are able under the keen intraplant competition of a commercial crop, to yield more grain, more leaf, more dry matter. Why? The breeder has no idea. Indeed, the answer to such a question will often be that it yields more because it has more ears, or more florets or more fertility or less abortion, which of course, is little more than a paraphrase of the statement that it yields more. Actually, what happened was that the breeder selected it because it yielded more, not that it yielded more because it was consciously bred to do so. Why does a modern wheat variety, whether in Greece or New Zealand, yield more than a variety of like maturity and disease resistance of fifty years ago? Because it either (a) fixes more carbon or (b) has a greater proportion of the carbon in the grain. Why? No one knows. Perhaps it has a different root system, better leaf arrangement and light utilization, more glume surface, or one of many factors affecting growth and photosynthesis. And, in particular, it has these desired characteristics when growing under the acute stress conditions of a commercial crop." □

V. Effect of Weed Density

Even cursory review of a portion of weed competition literature leads to the conclusion that increasing weed density decreases yield. However, the weed density-crop yield relationship diverges from linear. A few weeds usually do not affect yield; also, the maximum effect, total crop loss, obviously cannot be exceeded and usually occurs at less than maximum weed density. Weed competition can thus be represented by a schematic sigmoidal relationship (Figure 2). A curvilinear relationship was reported by Roberts et al. (424) who described the effect of naturally occurring annual weeds at densities of 65 to 315 plants/m² on yield of *Lactuca sativa* L. (summer lettuce). Very low densities were not included. The study clearly shows that marketable lettuce yield sinks to zero at less than maximum weed density. The same relationship applied to the effect of *Echinochloa crus-galli* on *Oryza sativa* (rice) yield (374).

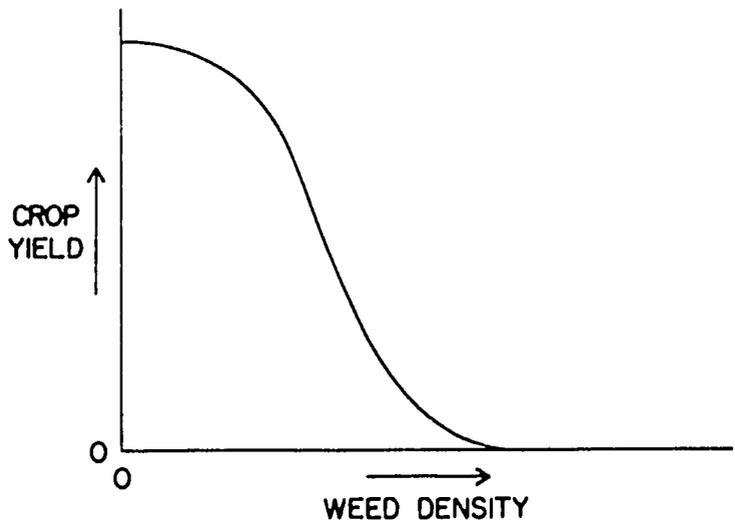


FIGURE II

A schematic sigmoidal relationship depicting the effect of increasing weed density on crop yield.

Data from selected studies depicting increasing weed density effect on crop yield appear in Table I. These data, plus other studies that could be cited (see specific crops), confirm the hypothesis that the relationship between weed density and crop yield is nonlinear over the range from zero weeds to a naturally achieved high density. A linear relationship emerged in a recent study by Coble and Ritter (141) evaluating *Polygonum pensylvanicum* competition in soybean. However, the highest weed density was omit-

TABLE I

The effect of increasing weed density on crop yield—selected studies.

Crop	Weed	Weed density	Percent yield reduction from control	Ref.
sugarbeet	<i>Kochia scoparia</i>	0.04/ft of row	14	548
		0.1	26	
		0.2	44	
		0.5	67	
		1.0	79	
soybean	<i>Brassica kaber</i>	1/ft of row	30	52
		2	36	
		4	42	
		8	50	
		16	51	
	<i>Xanthium pensylvanicum</i>	1335/A	10	42
		2671	28	
		5261	43	
		10522	52	
	wheat	<i>Avena fatua</i>	70/yd ²	22.1
160			39.1	
<i>Setaria viridis</i>		721/m ²	20	10
		1575	35	
cotton	<i>Sida spinosa</i>	2/ft of row	27	273
		4	40	
		12	41	
rice	<i>Echinochloa crus-galli</i>	1/ft ²	57	471
		5	80	
		25	95	
corn	<i>Setaria faberii</i>	½/ft of row	4	296
		1	7	
		3	9	
		6	12	
		12	16	
		54	24	

ted from the curve presented; had it been included the relationship probably would have been sigmoidal. Weatherspoon and Schweizer (548) found that one *Kochia scoparia* plant per 10 feet of row reduced sugarbeet yield 26% below a weed-free control plot.

A linear relationship would predict that one weed per foot of row would reduce yield ten times as much, which is obviously impossible. Similar logic fits each study in Table I; the data confirm a lack of linearity.

TABLE II

The competitive effect of four weed species on cotton grown on two soil types (90, 91).

Weed species	Weed density	Yield reduction	
		Sandy loam	Sandy clay loam
	*	(%)	(%)
<i>Xanthium pensylvanicum</i>	8	20	60
<i>Amaranthus retroflexus</i>	8	0	70
<i>Cassia obtusifolia</i>	8	25	40
<i>Ipomoea purpurea</i>	8	40	50

*plants/7.31 m of row

In two papers Buchanan and Burns (86, 87) added the complicating factor of soil type; identical densities of a weed can vary in competitiveness depending on soil type. Studies revealed that each of four weed species tested competed more aggressively with *Gossypium hirsutum* L. (cotton) on sandy clay loam soil than on sandy loam (Table II). The authors suggested that more favorable fertility and moisture relationships in the sandy clay loam soil could have accounted for the observed differences.

Triticum aestivum—Wheat

Two review articles published in 1970 summarized the "state of the art" for weed control in wheat (239, 363). Unquestionably competition from several weed species lowers yields of wheat and other small grains. Mukula et al. (357) surveyed 2,710 fields in Finland and found that soil type, temperature, water conditions, and preceding crop were the primary influences on distribution of 304 weed species. A partial survey of South Dakota (USA) wheat fields (172) identified a total of 48 weed species with a mean density of 35/ft.² Annual broadleaf species dominated, but *Setaria*

spp. were encountered most frequently. Trials in the U.K. (415) failed to demonstrate a clear relationship between wheat yield and number or species of broadleaf weeds present. One North Dakota (USA) study showed that weed control or its lack in a preceding crop affects weed population and yield in wheat (362).

Weed competition in cereals generally reduces crop vigor, tillering, head size, and kernel weight (119). Godel (206) found the primary effects were head size reduction and decreased tillering and that there was only a slight effect on kernel weight. In Canada, total crop losses attributed to weed competition ranged from 10 to 25% (200). In another study of 142 fields, a significant protein content increase in 22 of 60 fields developed when weeded and weedy plots were compared (201), but the effect on protein was not confirmed by other research (74).

According to Blackman and Templeman (63) cereals and annual weeds primarily compete for nitrogen and light. The researchers applied several rates of nitrogen to weed infested crops and found that weeds reduced crop growth less at higher nitrogen levels. Nitrogen significantly increased the number of tillers and seed yield of barley growing with *Brassica arvensis*; in some cases, yield of a weedy crop was greater than the weed free control.

Barley, Pavlychenko and Harrington (396) noted, was the most competitive small grain, followed by rye, wheat, *Avena sativa* L. (oats), and *Linum usitatissimum* L. (flax) in descending order, a ranking confirmed by other work (48, 49). *B. arvensis*, *Avena fatua*, and *Thlaspi arvense* were the most vigorous weed competitors studied. Their success was attributed to:

1. ready and uniform germination under adverse soil moisture conditions;
2. ability to develop a large leaf assimilation surface in the early seedling stage of growth;
3. large numbers of stomata;
4. a large mass of fibrous roots close to the soil surface, but deeply penetrating main roots.

Eight other weeds, including *Chenopodium album*, *Amaranthus retroflexus*, and *Polygonum convolvulus*, competed less vigorously. Removal of these and similar annual weeds before the crop was 4 inches tall usually avoided yield loss from competition (429). *Lappula echinata* was rarely serious and *Lepidium intermedium* posed no problem (396). Wheat developed a larger root system than *A. fatua* 5 days after emergence; however, their relative size reversed by 22 days. *A. fatua* produced more root tissue than any of the five cereals in this study.

Cereals compete with *A. fatua* only by dint of its slower germination. In a later study (397), the same authors found competition began under the soil surface when root systems mingled and water and nutrients became limiting. Barley competed more effectively than wheat because it provided a larger number of seminal roots 5 days after emergence and developed more crown roots by 22 days than any other cereal. Wheat's root system was 30 times larger than *B. arvensis* (which depressed wheat yield up to 40%), but wheat was more severely depressed by *A. fatua* which had a root area four times greater than wheat. All cereals grown alone had crown root systems and much larger root systems than when grown under the stress of intra- or interspecific competition. Cereals grown in 6-inch rows often failed to develop any crown roots. Intraspecific competition reduced total root system length 81 to 99 times in wheat, rye, and *A. fatua* when single plants grown in 10 ft squares were compared to 18 to 20 plants/ft in 6-inch rows (394). When wheat was drilled and *A. fatua* or *B. arvensis* was planted between crop rows, a further six- to tenfold reduction in total root length was observed.

Godel's 1935 study (206) indicated increased cereal seeding rates on heavy soils partially controlled annual weeds. He also advocated shallow, early seeding and use of fertilizer. Suomela and Paatela (499) found that fertilizer increased the number and average weight of weeds in irrigated and non-irrigated plots. Considering the specific competition between wheat and *A. fatua*, Molberg (349) confirmed that maximum benefit from fertilizer only occurred when the weed was controlled (Table III). The data paralleled those from Hannah showing as few as 10 weeds/yard² reduced yield 8% without fertilization, but up to 20% when plots were fertilized (225).

TABLE III

Yield of wheat as affected by fertilizer and *Avena fatua* (349).

16-20-0 fertilizer	<i>A. fatua</i>	wheat
(lb/A)	(g/m ²)	(bu/A)
0	36	27.2a
100	38	29.4ab
0	10	31.7bc
100	9	33.2c

Apparently nitrogen fertilization increases yields of both, but does not alter the proportion of *A. fatua* to wheat; however, phosphorus will increase wheat yield and reduce growth of *A. fatua* (456, 512). Therefore, nitrogen may increase yield, but it is not likely to affect crop-weed balance (512).

Chancellor and Peters (132) demonstrated that, a.) high densities of *A. fatua* are required to depress yield observably and, b.) that effects only become visible late in the wheat growth cycle. *A. fatua* affected yield in only three of seven experiments and in each case at a population greater than 150 plants/m². No significant yield reduction occurred at 20 to 100 *A. fatua*/m². Friesen (202) found 135 *A. fatua*/yd² reduced wheat yield 77.5% compared to 14/yd². Thurston (513) confirmed that *A. fatua* can be effectively suppressed by a dense crop of any autumn sown cereal in the United Kingdom, but even the densest stand did not completely suppress the weed. The effect was mainly due to decreased seedling growth.

In Canada Bowden and Friesen (74) obtained contrary results as 10 to 40 *A. fatua*/yd² reduced yields of wheat grown on either summer fallow land, or when ammonium phosphate was added to stubble land; also, effects became evident early in the growth cycle. (The rainfall and soil moisture patterns of the relatively wet U.K. sharply contrast with dryland Canada.) One winter fallow period can reduce *A. fatua* populations by 97%. Two consecutive fallow years have reduced it to less than 0.2/m² (411). Without added ammonium phosphate, 70 to 100 *A. fatua*/yd², a density approaching that in Friesen's study (202), were required to reduce yield. Soil fertility (nitrogen status?), Bowden and Friesen suggested, was a more important determinant of the effect of *A. fatua* on wheat than "moderate" densities (74).

Paterson (393) felt *A. fatua*-caused yield reduction depended on potential crop yield and that the greatest losses occurred in fields with highest yield potential. McNamara (Australia-333) found wheat yield was reduced linearly, up to 1.025 gm²day⁻¹ for the duration of competition up to jointing. His results do not hold that *A. fatua* exerts its greatest competitive effect early, as Bowden and Friesen's (74) do, nor that *A. fatua* has no effect at early crop growth stages (as Chancellor and Peters (132) proposed). Through comparison of results from several studies it can be deduced that *A. fatua* (74) causes more detriment to wheat yield than *P. convolvulus*, *B. arvensis* (119), or *Setaria* spp. (265).

Bell and Nalewaja (47, 48, 49) agreed that barley competes more vigorously than wheat, and wheat more than flax. *A. fatua* prevented these crops from fully utilizing soil fertility, but it did not affect crop quality. Densities of 70 and 160 *A. fatua*/yd² reduced wheat yield 22.1 and 39.1% respectively compared to a weed free control (49). Similar densities reduced barley yield 6.5 and 25.9%. Added nitrogen and phosphorus reduced yield loss in 2 of 3 years, but the crop could not fully utilize the available fertility. On fertilized plots *A. fatua* at 35 and 80/yd² reduced

wheat yield 8.4 and 11.6 bu/A respectively. On unfertilized plots, the same densities reduced yield only 2.8 and 5.3 bu/A.

Dew (161) developed a regression equation for cereal crop yield loss associated with varying densities of *A. fatua*. The ratio of the regression coefficient to the intercept (b/a) has been termed the competitive index (CI); using it, Dew confirmed that barley (CI = 0.021) is more competitive than wheat (CI = 0.031). A similar equation has been developed in the U.S.S.R. to show that yield increased inversely to the degree of weed infestation (584).

Two diverse locations, Australia and the Pacific Northwestern U.S., have reported the effects of *Lolium multiflorum* and *L. rigidum*. When *L. multiflorum* was well controlled wheat yields averaged 5,260 kg/ha, whereas untreated plots yielded only 870 kg/ha (6). When *L. multiflorum* density increased from 0.7 to 93/m², yield loss rose from 0 to 4,100 kg/ha (25). A greater loss occurred at high nitrogen fertilization rates (168 kg/ha) as opposed to low (56 kg/ha). The authors concluded that nitrogen constituted a poor investment in the absence of effective weed control. They also noted that percent yield reduction tended to be higher in semidwarf wheat cultivars (Table IV).

TABLE IV

Percent yield reduction caused by *Lolium multiflorum* at two densities with two cultivar types (25).

Wheat cultivar type	Yield reduction at densities of	
	40/m ²	96-107/m ²
	(%)	(%)
tall	19-26	28-31
semidwarf	24-26	37-39

The Australian report (418) suggests the same problem when *L. rigidum* competes with wheat. Although yield reductions of 23.1 to 47.8% were observed at a weed density of 1,500/m², no evidence emerged to indicate that cultivars of semidwarf parentage were more affected than traditional cultivars.

The competitive ability of some *Brassicaceae* has been studied in wheat. Nearly a 50% yield loss has been observed with 239 *B. arvensis*/m² (363). Densities of *B. arvensis* from 10 to 400/yard² adversely affected growth, tillering, and yield of wheat at planting rates of 1, 2, or 3 bu/A (119). Wheat yield was unaffected by *Saponaria vaccaria*, but decreased 14% due to 276 *B. kabera*/m² (13). *B. kabera* had a detrimental effect on *S. vaccaria* when grown together in wheat. Seed and dry weight of *S. vaccaria* were nearly halved by 190 *B. kabera*/m², and grain yield was reduced 38% (15).

S. vaccaria at 314/m² had little effect on *B. kaber*. Competition of the two species was not additive and the effect of *B. kaber* obscured *S. vaccaria* when they occurred together. The latter weed became a problem after 2,4-D successfully controlled *B. kaber* (15).

One *Descurainia pinnata*/ft² may reduce winter wheat yield 10% (562). In three years, the average yield was 28, 21, and 9 bu/A from a weeded check. One weed/ft² reduced yield 10, 6, and 0% respectively, while six weeds/ft² cut yield 32, 12, and 0%. The last year was a very dry year as shown by a weed free yield of only 9 bu/A.

Approximately 50% of the competitive effect of *Chorispora tenella* occurred during winter months, before spring weeding, when the weed formed a low growing $\frac{3}{4}$ to 6 inch rosette of leaves (501, 502). Total yield loss from one, three, or nine weeds/ft² ran 11.1, 16.8, or 20.3 bu/A (501). *Amsinckia intermedia* produced the same level of competition (503).

Three studies of competition with *Setaria viridis* (10, 11, 12) and one with *S. glauca* (sp. n. *lutescens*) (265) have been reported. At 20 lb nitrogen/A, *S. viridis* had no effect on wheat height, but did decrease height at 3 lb nitrogen/A (10). Yield was reduced 20% (not significant at $P = 0.05$) by 721 weeds/m² and 35% by 1,575/m² (10). *S. viridis* at 2,200 to 5,700/m² in a second study decreased ($P < 0.01$) wheat yield by 40% compared to weed free plots. The wheat seeding rate did not affect wheat yield or total shoot dry matter of the weed (11), nor did seeding method affect the ability of wheat to compete with *S. viridis*. Wheat yielded less when seeded with a one-way disc drill as opposed to a standard grain drill but the affect of the weed was greater when wheat was seeded with a drill so the net affect of seeding method on weed competition was negligible in this study (12).

Densities of zero, three, six, and nine *P. convolvulus* grown with three wheat plants/pot did not reduce wheat yield if competition ended 10 days after crop emergence. Yield was affected by all densities when competition lasted 20 days or longer (31). *P. convolvulus* competed strongly in spring wheat because it germinated early, rapidly developed leaf area, and increased its dry weight (173). Wheat out competes *P. convolvulus* in terms of dry matter production (190); wheat when grown alone, increased in dry matter and nitrogen with increasing soil moisture, but not when competing. The weed used less water to produce a unit of dry matter when grown alone, but became intermediate in water use under competitive conditions.

Heavy stands of *Lepidium campestre* reduced wheat yield 45% and lesser infestations exerted proportionately lower effects (125). *Agrostis gigantea* and *Agropyron repens* competed most vigorously

in late planted wheat or in sparse stands, the former being the better competitor of the two. *A. repens* manifested its strongest growth when planted early. Late planting, relative to wheat, halved its shoot growth and inhibited its rhizome formation (575). *A. repens* reduced grain weight 13% in spring wheat, but had no effect on spring barley grain weight (144), though barley yield fell nearly 16%.

Chondrilla juncea governed cereal crop response to nitrogen. Competition was most severe at low nitrogen levels while only minor at high levels. When other nutrients were plentiful, response to nitrogen application equalled response to MCPA. Early nitrogen applications provoked a yield response; treatments later in the season only increased grain nitrogen levels (359).

When *Bromus tectorum*, primarily a dryland wheat and wheat-fallow problem weed, emerges with, or within one week of, wheat it can depress yield as much as 20 to 32%. It does not affect yield when it emerges two weeks or more after wheat (560). Removing *B. tectorum* from fall planted wheat by early spring held yield reduction to 6 percent. When it remained until harvest, 40% of yield was lost at weed densities of 108-160/m² (436). Fallow tillage with a moldboard plow reduced weed stands by 95% compared to using a sweep cultivator. Use of a one-way disc thinned weed stands by two-thirds. Tillage with a one-way disc, combined with herbicides, was advocated as the best control method (109). Rydrych and Muzik (437) showed that *B. tectorum* ranks as the premiere weed problem in winter wheat areas receiving 15 to 55 cm of rainfall annually. The most severe yield reductions occurred in the 30 to 50 cm precipitation zone. Winter wheat growing on a light soil receiving 25 cm/year precipitation was reduced 28% by fewer than 54 weeds/m². With 55 cm of rain, on a silt loam soil, yield suffered a 92% reduction from 538 weeds/m². The weed density was ten times greater, but not the effect on yield. Yield losses magnified under the higher rainfall regime because of the greater weed population (437).

One study of *B. secalinus* competition in wheat is available (126).

Hordeum vulgare—Barley

Pavlychenko (395) reported that barley competed with *Avena fatua*, *Brassica kaber*, and *Polygonum convolvulus* more effectively than either wheat or oats. Increasing the barley seeding rate reduced initial *A. fatua* populations as did barban application (407). Barley yield per unit area increased when *A. fatua* competition was reduced. Pfeiffer and Holmes suggested that crop competition and barban acted independently and the effect on yield was

simply additive (407). Number of culms and yield were increased in both field and growth chamber studies (331) by nitrogen, barban application, and delay in seeding *A. fatua*. However, nitrogen did not increase yield of *A. fatua* in the field. A reciprocal relationship between culm number and yield (331) demonstrated competition. Competition between barley cultivars prevailed primarily for water and secondarily for nutrients (231), a condition that seemed to hold for all intraspecific competition in barley species with similar morphology.

Mann and Barnes experimented with competition between barley and six weed species. Yields of crop plus weed has a tendency to reach a maximum for a given total density of plants/soil area. *Spergula arvensis* and *Matricaria inodora* were limiting to barley and limited by barley (321). The same was true for *Agrostis gigantea* (323) and *Trifolium repens* (325) which also reduced spring oat yield (399). The effect of *Holcus mollis* depended on the seeding rate of barley and which plant became established first (322). If the weed was established and the barley stand thin, yield losses up to 100% could occur. Competition with *Stellaria media* reduced barley yield, but because of the weed's rapid early root development barley did not affect it (324).

With a constant amount of weediness from *S. arvensis*, *Anthemis cotula*, *H. Mollis*, or *A. gigantea*, increasing barley density diminished yield losses (321, 322, 323). The combined weight of barley and variable weed populations rarely equalled barley alone without weeds. In the Mann and Barnes studies, barley seeding rate was critical to its competitive ability (321, 322). They proposed that any reduction in barley yield due to weeds at nitrogen levels in excess of those which increased yield, must arise from competition for root "space" (321). All variables, with the exception of light, were optimum, but because weeds were shorter than barley, light could have been limiting.

In a later, and complementary, effort, Fogelfors (195) studied *S. media*, *S. arvensis*, *Polygonum aviculare*, *Veronica agrestis*, and *Viola arvensis*. Barley suppressed growth of *S. Arvensis* 93% and *P. aviculare* 95% as these species were poorly adapted to low light conditions under the barley canopy. However, *P. aviculare* still reduced barley yield. The dry weight of *S. media* was reduced only 73% because it has higher physiological adaptability to low light conditions; like the previous species pair, however, its vegetative and generative phases reside in the lower parts of the crop. The other two species were intermediate in their response.

Aspinall and Milthorpe (35) found barley growth was not affected by even dense stands of *Polygonum lapathifolium*, but that the barley greatly restricted the weed. Barley's advantage was

attributed to the relative embryo size of the two seeds. These researchers concluded that intraspecific competition studies to understand the influence of density must report growth over time rather than weight-density relationships at given points in time (35). *Fagopyrum tataricum* at 50/yd², if removed before barley had two to three leaves, did not reduce barley yield but did suppress it if left beyond that point (523).

Work by Scragg and McKelvie (455) suggested that the increasing weed density effect on barley related to species. *Galeopsis* spp. had little effect, but *A. fatua* severely decreased yield. *Agropyron repens* posed less serious competition than *A. fatua* because *A. repens* emerged later than the crop. Barley's plasticity allowed it to adjust for variable numbers by tillering, whereas *A. fatua* produced single stem plants limiting its impact directly to plant number. A "no effect" threshold of 10 to 20 *A. fatua* panicles/m² was suggested (455). Barley yield, when compared to plots with 80% weed control, fell more than 40% due to 720 *A. fatua*/yd² (202).

Bell and Nalewaja (47, 49) found barley more competitive and more responsive to fertilizer than wheat. Eighty *A. fatua*/yd² did not reduce barley yield from fertilized plots, but lowered unfertilized plot yield 6.7 bu/A; the reduction was less than for the same density in wheat. Adding fertilizer nearly eliminated the effect of *A. fatua* in barley.

Linum usitatissimum—Flax

Mixed natural weed stands reduced flax yields 22 to 31% during three years in Manitoba, Canada (200). Flax losses consistently exceeded those in wheat, barley, or oats (74). Though relatively few, the studies of weed competition in flax have clearly defined the problem for four weed species: *Brassica arvensis* (120), *Polygonum convolvulus* (212, 213), *Saponaria vaccaria* (9, 14), and *Avena fatua* (46, 50, 51).

Burrows and Olson concluded that control of 10 or more *B. arvensis*/yd² increased grain yields (120). Some additional yield loss occurred between 10 and 25 plants/yd², but 100 *B. arvensis* caused no further loss. The weed caused most damage when present during the seedling stage of flax due, in part, to stand reduction and decreasing the number of basal branches and seed bolls/plant. The weed also reduced the iodine number which measures the number of unsaturated linkages and thus oil quality.

P. convolvulus effectively competed with flax by using moisture more efficiently thereby gaining more nutrients (213). Flax

yield responded quadratically with maximum reduction at densities of 10, 15, and 20 plants/ft². Actual yield loss increased as the yield potential of the crop-soil location rose. Percent yield reduction depended on flax stand and the crop's ability to handle competitive stress. Field studies showed reduced losses by increasing flax seeding rate and removing weeds early (Table V) (213). Thus, a 25% maximum yield loss occurred at a 14 lb/A seeding rate, but decreased to 10 to 13% at 70 lb/A. The increasing plant density effect confirms the later finding of Alessi and Power (8) that weeds reduced yields less when flax crops were planted with narrow row spacing (a range of 7.5 to 30 cm). Fertilizer increased yield less at high seeding rates (212, 213, 457), and generally doubled dry matter production of *P. convolvulus* which benefitted more from fertilization.

TABLE V

The relationship of flax seeding rate and yield reduction due to *Polygonum convolvulus* competition in North Dakota, USA (213).

Location	Flax seeding rate	For all <i>P. convolvulus</i> densities	
		Flax yield	Yield reduction
	(lb/A)	(bu/A)	(%)
1	14	22.6	24.7
2	14	10.8	25.0
1	42	25.7	14.6
2	42	13.8	18.3
1	70	26.5	10.1
2	70	15.3	13.1

Growth chamber studies revealed that crop-weed competition reached maximum intensity at 30 to 60 days, the period of greatest dry matter production for both species. These data matched field information showing competition up to the late flower stage (which continued to the well developed boll stage) causing yield losses nearly equal to full season competition. Weed competition in the growth chamber for 30 to 60 days decreased flax dry weight 52%, but only 29% for *P. convolvulus*. Flax nitrogen uptake decreased more; the researchers observed no difference in phosphorus uptake (213).

Alex (9, 14) studied competition caused by *S. vaccaria* noting that as few as 30 to 37 plants/m² reduced flax yields; four hundred weeds/m² reduced yield 61% and 1000 increased losses to 73% (9, 14). The crop was unaffected by one, four, or 11 weeds/m². *S. vaccaria* did not affect flax stand, but did reduce basal branching and inflorescence size. Phenologically the two plants are very

similar as they emerge at the same time and grow at equal rates, though *S. vaccaria* matures a week or two earlier in Canada. The investigator validated *S. vaccaria* being less competitive than *B. arvensis*. Yield of weed seed and straw increased as density increased up to 127 plants/m². Maximum weed seed production nearly equalled flax seed yield in weed-free check plots (9).

Bell and Nalewaja studied flax losses due to *A. fatua* competition (46, 50) and the effect of competition duration (51). Flax yield fell as the competition period increased. Full season competition from 80 *A. fatua*/yd² reduced flax yield 60% (9.4 bu/A) and 160/yd² reduced yield 82% (21.5 bu/A) at one location and 86% (16.1 bu/A) at another (50). Reduced number of branches and flax bolls/ft² accounted for nearly 91% of the loss; reductions of weight/1000 seeds and stand accounted for the balance.

A. fatua densities as low as 10/yd² usually depressed yield, and 20 or 40/yd² reduced yield 25 and 42% respectively (50, 74). *A. fatua* competition caused flax to mature 3 to 6 days earlier (depending on weed density) and lowered the crop's oil quality (50). Competition until the four to five leaf stage of flax reduced yield 15%, whereas with full season competition loss ballooned to 75% (51). Competition lessened yield continuously from emergence to heading. The most serious competition occurred early in the growth cycle with no further decrease after heading (74). At any growth stage, higher weed densities always caused greater yield cuts. Higher densities also reduced yield at a faster rate (51).

Oryza sativa—Rice

Several valuable summaries of weed control in rice include information concerning weed competition effects (330, 472, 474). Smith et al. (474) reported 35 to 74% losses due to weeds in the U.S. Others acknowledged losses in the same range (134, 136, 340, 376, 460, 471, 500). Jennings and colleagues, in three studies (277, 278, 279), and Kawano and Tanaka (287, cited in 286) studied the physiology of competition, its genetic control, and the implications of intraspecific competition to cultivar evolution. Most other studies have been agronomic rather than physiological in that they asked what happened rather than why.

Kawano et al. (286) proposed that evolution of cultural methods has caused cultivar evolution and a consequent loss of competitive ability. Intraspecific competition between rice and weeds correlated with rice's spacing response. They suggested control through genetic factors rather than physiological processes.

Competitive ability negatively correlated with nitrogen response; as a result, strongly competitive cultivars tended to yield poorly under improved agronomic conditions. At low nitrogen levels plants compete first for nitrogen. With adequate nitrogen plants first compete for light. The high yield of IR-8 (rice cultivar) under fertile soil conditions often coexists with increased weed weight/unit area suggesting that weed control becomes more important under high, compared with low, soil fertility (159), a state that has been confirmed (134). Rice density does not affect weed species distribution. However, the number of weeds/unit area fell 49% under high crop density conditions (232). Density affected *Cyperus rotundus* more than other species. *Portulaca* spp. evidenced virtually zero response to crop density. Soil puddling reduced weed number 70% under high crop density, and 81% with low density (232).

Weed control typically experienced greater success with a short lodging-resistant cultivar than a tall lodging-prone cultivar.

Research results concur that the full impact of weed competition occurs early in the growing season. Exact length of the so-called "critical period" (discussed in Chapter VI) varies. In India, practically the entire weed competition impact occurred due to weeds left past the first 20 days after emergence (460). The critical period occurred 10 to 20 days after emergence; yield increased as the weed-free period lengthened. For the Philippines, yields suffered when weeds were left beyond 40 days (525); the period extended to 50 to 60 days in Korea (391). Because transplanted rice has an initial growth advantage, weeds are less detrimental than in direct seeded rice (26, 460). In Taiwan yields of first and second crops were depressed about equally (134).

Several authorities agree that the title of world's worst rice weed belongs to *Echinochloa crus-galli* (249). Chisaka found a linear relationship between rice yield and density of *E. crus-galli*. When *E. crus-galli* yielded 100 g/m² (dry weight) rice yield decreased to 20% of the control. Cultivars competed more effectively as their period to maturity increased. In one study (473) competition for 10 to 20 days did not reduce yield; competition for 40 days or longer, however, reduced yields of two cultivars while a third strain only sustained competitive loss after 60 days or longer.

Noda et al. (373, 374, 375) encountered a slight curvilinear relationship between *E. crus-galli* densities and rice yield while Chisaka (136) found a linear relationship. However, Chisaka considered densities up to a 1,000 g/m² maximum. The addition of greater densities (up to 1,500 g) in the study by Noda et al. (374) undoubtedly accounts for the deviation from linearity. The curvilinear relationship implies that weed competition yield losses

reach maximum near 1,500 g/m² of *E. crus-galli* and that denser populations will not further decrease yield.

Two critical competitive periods have been identified for transplanted rice. The first, between 4 and 6 weeks after transplanting, corresponds to the period of maximum tillering and caused the greatest damage by reducing the number of panicles. The second occurred during the twelfth week, or early ripening stage, and reduced grain weight (139, 374).

Rice yield reduction related more to weight than number of *E. crus-galli*. Crop plants under competitive stress produced fewer tillers and fewer panicle bearing tillers; they also manifested smaller panicles, delayed heading, and increased plant height (374).

Twenty *E. crus-galli*/m² competing from the seventh to the fortieth day after emergence in Philippine lowland rice reduced yield 20%; 40 plants/m² reduced yield 40%. However, there was no further reduction from 60, 80, or 100 plants/m². Keeping the crop weed free from the seventh to the twentieth day proved more important than weeding during the following 20 days (26, 319). Weeds emerging 40 days after transplanting or later did not affect yield in this (319) and other studies (159, 340, 471).

Smith (470, 471) studied *E. crus-galli*, *Sesbania exaltata*, *Aeschynomene virginica*, and *Heteranthera limosa*. *E. crus-galli* and *H. limosa* lowered rice yields early in the season. Even though they emerged with rice, the other two species competed more effectively

TABLE VI

The interaction of rice stand and density of *Echinochloa crus-galli* (471).

Rice plants/ft ²	<i>E.</i> <i>crus-galli</i> plants/ft ²	Yield reduction (%)
3	0	0
3	1	57
3	5	80
3	25	95
10	0	0
10	1	40
10	5	66
10	25	89
31	0	0
31	1	25
31	5	59
31	25	79

late in the season. Smith's studies emphasized the role of biological variability and the necessity of repeating competition experiments. *E. crus-galli* reduced rice yields as follows: one year out of three when competition lasted 15 to 20 days; two out of four years for competition lasting 22 to 26 days; three out of four years when competition extended 37 to 40 days; all four years for weeds present 51 days or more (471). Weeds exerted more competition in thin rice stands than in vigorous ones (Table VI). Even one weed/ft² with an optimum rice density of 31 plants/ft² reduced yield 25%. All the data reviewed support the frequently encountered contention that *E. crus-galli* is not only widespread, but a most detrimental rice weed.

A recent effort compared the competitive ability of *Echinochloa colonum* in direct seeded, lowland rice (340). While the weed's average natural density in direct seeded, Philippine rice equals 280 plants/m² (2.8×10^6 /ha), only 80 plants/m² present during the first 40 days after planting were sufficient to depress drilled rice yields.

Because *E. colonum* average populations greatly exceed the 80 plants/m² critical density, it poses a serious problem even though not the vigorous competitor *E. crus-galli* is. *E. colonum* produces more tillers than rice and yields up to 42,000 seeds/plant. Observations indicated no effect on number of rice tillers, but an 18% decrease in leaves produced. The weed grew 7 to 8 cm taller than the crop suggesting competition for light (340).

S. exaltata grown for 4, 8, 12, or 15 weeks after emergence reduced yields 2, 4, 9, and 19%, respectively. Densities of 5,445, 10,890, 21,780 or 43,560 weeds/A caused 8, 14, 26, and 39% yield drops. *S. exaltata* and *A. virginica* exhibited strong late season competitiveness, but *S. exaltata* more so due to taller growth. Neither weed competed if removed before it shaded rice (470, 471).

H. limosa, during one year, reduced rice yield when present for as little as 2 to 4 weeks; in another year it needed 8 weeks to affect yield. A 5-year average mandated removal at 4 weeks. When present for 2, 4, or 8 weeks, or all season, yields decreased 5, 14, 28, and 21%, respectively (470, 471). *E. crus-galli* out competed all other weeds in Smith's study as well as *Monochoria vaginalis* (26, 319).

E. crus-galli bears a morphological similarity to rice, an important clue to the weed's competitive ability. It has also been suggested that, because rice roots are distributed through all soil layers, competition for nitrogen was more vigorous (26), a conclusion at odds with Matsunaka's (330).

Relatively low densities of *E. crus-galli* affect rice yield (471) while *M. vaginalis* must approach 100 plants/m² from the seventh

to fortieth day before affecting yield, and then only reducing it 16% (319). Allowing the same *M. vaginalis* density to remain until crop maturity reduced yield 25%. *E. crus-galli* in a natural population of 135/m² reduced rice yield 72% compared to a 35% loss due to *M. vaginalis* at 366/m² (319). Whereas *E. crus-galli* reduced yields of first and second crop rice about equally, *M. vaginalis* and *Cyperus difformis* caused more injury to a second crop because higher air temperatures more favorable to their growth prevailed (134). *M. vaginalis* competed more effectively per unit of plant weight than *E. crus-galli*, but the latter grew 60 to 80 times larger causing it to be a more effective competitor on an individual basis (26).

In a pot experiment 100 to 300 *C. difformis* plants/m² reduced rice yield 49 to 81, and 57 to 90%, respectively. Higher fertility and temperature accelerated yield loss (134). In later studies (500) with

TABLE VII
Yield reductions due to weeds in rice.

Weed	Rice cultivar	Yield reduction (%)	Weed density	Reference
annual grasses	IR-8			
	—high fertility	24.5	200 g dw/m ²	159
	—ordinary fertility	30.0	200 g dw/m ²	
annual grasses	H-4			
	—high fertility	32.8	200 g dw/m ²	159
	—ordinary fertility	26.2	200 g dw/m ²	
annual grasses	Shiranuhi			
	—high fertility	19.0	200 g dw/m ²	374
	—ordinary fertility	18.2		
annual grasses	Nihonbare	23.0		330
		20.0		135
annual grasses, sedges and annual broad-leaf species	Ratna	42-65	162 plants/m ²	460
<i>E. crus-galli</i>	Unknown	20	20 plants/m ²	319
<i>Monochoria</i>		40	40 plants/m ²	
<i>vaginalis</i>		16	100 plants/m ²	

*dw = dry weight

C. difformis, full season competition impaired yields 22 to 43%, again with greater reduction at high fertility (500). *C. difformis* creates a serious weed problem in direct seeded rice, but not in transplanted rice because of the latter's growth advantage. Its greatest effect occurs at pre-tillering and tillering. Removal prior to tillering increased yield, whereas removal after tillering did not often affect yield. Swain et al. (500) proposed a linear relationship between rice yield and duration of *C. difformis* competition with a yield reduction of 64.4 kg/ha for each day of competition up to tillering at high fertility, but only 27.9 kg/ha under low fertility conditions.

Grain yield of drilled and broadcast upland Philippine rice dwindled 43 and 41% due to competition with *Cyperus rotundus* (376). Application of nitrogen benefitted *C. rotundus* more than rice. The weed's growth, development, and competitive ability increased with increasing nitrogen levels enabling it to compete more vigorously for water and further reduce light transmission to the crop (377). The authors concluded that weed control was more important with high, as opposed to low, levels of natural or supplemental fertility.

Table VII presents selected data for weed competition-caused yield reductions in rice. Most studies encountered reduction magnitudes in the 20 to 30% range. Not all work found greater losses taking place at high fertility.

Zea mays—Corn

In an early (1912) and perceptive report Cates and Cox (127) stated that weeds make corn cultivation necessary. Further cultivation provided no additional benefit to corn beyond weed control. Observable practice suggests that most growers do not believe this, but available competition data support the view of Cates and Cox.

Meggitt (339) and Nieto (370) have written valuable background papers on weeds in corn. Nieto (370) cites a U.S.S.R. paper which includes the interesting, and almost heretical, observation that *Hibiscus trionum* appeared to favor corn production. Plots with the weed actually produced slightly more than uninfested plots.

Several reports address the proper timing for weed control. In Mexico, corn with the genetic potential to produce 5,000 kg/ha produced only 2,500 kg/ha if weeds were not controlled for the first 40 days after crop emergence (370). However, in the high valleys of Mexico, up to 9 weeks of freedom from mixed annual weed competition was required after corn emergence or yield waned (7).

Another study, conducted in Mexico's wet tropics, showed that 4 to 5 weeks of control were essential, but thereafter shading became an adequate control device (205). The crop grew unfazed by weeds present for the first 2 weeks after emergence; yields sank 56, 73, or 84% when weeds remained for 3, 4, or 5 weeks after crop emergence.

The first 2 to 3 weeks after emergence were identified as the critical period in New Jersey (U.S.) (316). During this span weeds produced 15 to 18% of their total growth while corn produced only 2 to 3%.

A report from Canada suggested that the most severe *Chenopodium album* competition resulted when corn was tasseling even when nitrogen was limiting (19). Li (316) noted far less competition duration effect at low fertility. No yield reduction from competition occurred for 2 weeks, but a 15 or 22% reduction was noted after competition for 3 to 5 weeks.

Bunting and Ludwig (102) emphasized the need for timely weed control by showing that weed competition periods for 2 to 4 weeks during early crop growth reduced final yield. Several other studies confirmed the need for weed control within 5 to 6 weeks after crop emergence; the data indicate that competition throughout this period equates to competition for the entire season (463, 485, 527, 573).

Of the several reports focusing on weedy grass competition in corn, most concern *Setaria* spp. Staniforth described several factors involved in patterns of *Setaria* spp. competition in corn (485). The more important observations:

1. soil moisture competition was important during summer months;
2. nitrogen fertilization minimized competitive effects;
3. *Setaria* spp. were less competitive as corn plant densities increased from 12 to 24 thousand/A, but greatest weed losses materialized at corn populations that generated optimum yield when weed free (also see 193).

In other work Staniforth showed that yield losses doubled for late maturing, as opposed to early maturing, hybrids and that high rates of nitrogen fertilization accentuated the difference (481). Weed competition severity peaked in late summer due to mature *Setaria* spp. that emerged with the crop. Apparently early maturing hybrids had passed a critical period in their growth while late hybrids had not.

S. viridis reduced yield a minimum of 5.9 and a maximum of 17.5% at varying densities (463). It was less competitive than *C.*

album which reduced yields 12.6 to 38.1% at varying densities (463). Loss in crop yield virtually equalled the weed yield increase.

Fifty *S. faberii* plants/ft of corn row in a 4-inch band reduced yield 25% (294). Yield slumped 8, 9, 12, or 15% due to 1, 3, 6, or 12 weeds/ft of row. On an individual plant basis *S. faberii* offered less competition at all densities than *Amaranthus retroflexus*. The densities used were not identified and preclude an exact relationship, but approximate comparison indicates that 1, 3, or 12 *A. retroflexus*/ft of row reduced yield 15, 27, or 36% (294).

S. faberii seeded 3 weeks or more after corn and in a band over the crop row did not affect yield (297, 298). The weed, although not competitive when seeded 3 weeks after corn, produced 500 lb/A dry weight; all its plants contributed seed. When weed-free corn yielded 144 bu/A, *S. faberii* depressed yield 1, 2, 5, 7, and 18 bu/A when removed at heights of 3, 6, 9, or 12 inches, and at maturity (299, 300). Yield did not waver until *S. faberii* reached 9 to 12 inches heights. As can be seen, full season competition was most severe. Although yields shrank at very low weed densities, high densities were not totally destructive. In one experiment (296) 54 *S. faberii*/ft of row weakened yield 25%.

Weed control was required for 2 to 3 weeks after corn emergence when competing with *Panicum dichotomiflorum* or *Digitaria sanguinalis* (527). Corn, 3 weeks postemergence, suppressed weeds. Crop and weeds primarily competed for moisture.

A nearly solid stand of *Amaranthus hybridus* (10.2 to 15.2 cm wide over the row) reduced maize yield 36% (352, 353). Total dry matter yield/unit area held nearly constant; the increased weed dry weight balanced the loss in corn. Weeds left for 10 weeks after crop emergence—the period coincident with the corn's silking stage—caused greatest yield losses. These reductions measured approximately 12%, more than half the total season loss.

Rottboellia exaltata emerging with corn and removed within 8 weeks did not affect yield. Weeds at 42 plants/m² reduced yield if left for 12 weeks (507). The weed, when sown 2 or more weeks after crop emergence, did not affect yield. Grain and total yield decreased and weed yield increased as weed density increased from 10 to 50 plants/m² on irrigated and unirrigated land. Yield was not affected by increasing corn density or nitrogen fertilization. Corn yield was increased by irrigation but weed yield was not. Crop and weeds primarily competed for light, and as few as 10 to 15 weed plants/m² decreased yield (507). The duration of competition before yield loss occurred was longer with *R. exaltata* than that reported for other weeds.

One study reported that heavy (undefined) infestations of *Cirsium arvense* caused great (undefined) yield reductions (184). Competition for water was pivotal; little competition for nutrients materialized other than for nitrogen.

Several reports have treated the role of nutrients in corn-weed competition. Ruinard (cited in 370) showed that fertilization increased corn yield 47% and weed control increased it 265%, emphasizing the importance of weed control and the possible role of fertility. *Cyperus rotundus* may not depress yield of corn grown in the humid tropics, even when population approaches 12 million/ha (370), if sufficient fertilizer is used. Adequate nitrogen fertility permitted corn to more effectively compete with *S. viridis* and *S. lutescens*. Increments of nitrogen increased corn yield two to three times more than *Setaria* spp. (372, 479). Corn yield reductions due to mature *Setaria* spp. averaged 20, 14, and 10 bu/A with 0, 70, and 140 pounds of nitrogen/A, plus a uniform 300 lb/A of 0-20-20 fertilizer (372, 479). Corn and *A. retroflexus* responded to phosphorus; crop plants in plots with low phosphorus endured weed competition better than when phosphorus was added (528). Even at high rates of fertilization, *A. retroflexus* competed strongly; Vengris (528) questioned the feasibility of maintaining high yields by fertilization without weed control.

Others have reported that competition in corn mainly centers on nitrogen and moisture, but sufficiency of each does not eliminate competition (304).

One report concerning competition for light indicated that low light levels early in the growth cycle affected corn growth twice as much as *A. retroflexus* (496).

Burnside et al. (118) studied the effect of weeds on harvesting efficiency as opposed to early competitive loss. Widely varying weed densities desiccated by freezing did not reduce harvesting efficiency in corn or other row crops. Average gathering losses were 2% coupled with an additional 1% threshing losses. Some of these losses were attributed to harvest delay while awaiting freezing.

Sorghum bicolor—Sorghum

In 1970 Phillips (409) estimated that annual sorghum grain yield losses due to weed competition reached 20 to 40 percent. Water supply exerts a tremendous influence on all sorghum-weed competition. Under low rainfall (less than 160 mm/year) one weed per 91.5 cm of row (51 cm wide) prevented grain production (408). Even under more favorable moisture relations one weed per 61 cm of row reduced yield approximately 40% and one per 30 cm reduced

it more than 50%. The central importance of competition for water has been emphasized by several authors (6, 149, 191, 266, 409, 494, 565). Wiese et al. (565) obtained a higher yield for irrigated sorghum in narrow rows without cultivation than in wide rows with cultivation. The reverse was true on dryland where plants in wide rows were more able to compete for limited soil moisture. Mann (326) found seeding rates greater than 4 lb/A reduced grain yield. He concluded that plant populations were a more important determinant of yield than row spacing.

Wiese studied sorghum's competitiveness with ten annual grass and broadleaf weeds (in pots) and found *Amaranthus palmeri* was the most competitive weed (563). In a later study (524) four *A. palmeri*/ft. of row reduced grain yield. Five weeds/ft of row reduced yield 22%, while zero cultivation (with weeds overall) reduced yield 48%. *A. palmeri* was more vigorous in, and detrimental to, sorghum planted early. Weeds that remained 2 to 4 weeks after sorghum planting reduced yield. *A. palmeri* neither emerged nor grew in sorghum that had been growing for 28 days.

In Kansas (USA), *Sorghum bicolor* and forage sorghum spaced 15, 30, 45, or 90 cm in the row reduced grain yield (531, 532). Weeds 45 cm apart reduced yield 73 to 82% the first year and 88 to 93% the second year; 90 cm spacing reduced yield 65 to 70%. Panicle size was the most important determinant of yield which was inversely correlated with several other plant parameters including leaf area, culm length, culms/plant, panicles/culm, seeds/panicle, and amount of light received at the canopy. The authors reported the number of grains/panicle increased 16 to 20 times as weed density decreased from one/15 cm of row to weed-free (532). Other studies have cited the greatest effect of early weed competition as a reduction in number of seed heads initiated (tillering) (113).

Feltner et al. studied competition from *Setaria lutescens* and *Amaranthus tuberculatos* cited as *Acnida altissima* (tall water-hemp) in Kansas (191, 192, 266). Natural, full season *S. lutescens* infestations produced 2,200 to 2,300 kg of weed dry matter/ha. Each 100 kg reduced sorghum grain yield by 64 kg/ha, primarily due to a reduction in number of seeds/head. Competition peaked during a year with above average rain and supplemental nitrogen fertilization. Competition provided by *A. altissima* (192) also primarily influenced seed size. While *S. lutescens* reached maximum dry matter production between 6 and 10 weeks after emergence, *A. altissima* continued to grow and, therefore, presented a greater threat. An inverse relationship existed between duration and density with duration of competition more important at lower densities. Competition of either weed for longer than 6 weeks reduced yield. Hurst (266) earlier reported that *S. lutescens* compe-

tition for 6 weeks after emergence reduced grain yield 28%. Full season competition reduced yield 53% while competition for 10 weeks reduced yield 72% (due to crop damage from weed removal at 10 weeks) (266). Hurst (266) and Hurst et al. (267) reported that *A. altissima* competition for 6 weeks, 10 weeks, or full season reduced yield 39, 78, or 82%. They also proposed that even though *A. altissima* produced greater total losses, *S. lutescens* was more competitive. *A. altissima* at 210 plants/10 ft² produced 3,594 lb of weed dry matter/A while *S. lutescens* produced 2,042 lb. Sorghum yields fell 45 lb for each pound of *A. altissima* dry matter versus 64 lb for each pound of *S. lutescens*. Thus, *S. lutescens* stood as more competitive on a per plant basis. Though no further reports were issued, the same researchers (266, 267) indicated that *Abutilon theophrasti* and *Ipomoea hederaceae* or *I. purpurea* competed equally with sorghum.

Among several reports evaluating the extent of weed damage, Wiese et al. revealed that uncontrolled annual broadleaf and annual grass weeds reduced yield 8 to 41% (in the U.S. state of Texas). Weeds germinating with the crop were most detrimental (565). In another U.S. state, Nebraska, full yield developed when weeds were removed 1, 2, or 3 weeks after planting. When weeds remained for 4, 5, 6, or 8 weeks after planting, yields suffered (104, 112). One conclusion: postemergence cultivations or herbicide application should not be delayed beyond 3 weeks after planting. However, weeds emerging more than 4 weeks after planting did not reduce yield (113, 115), so neither herbicides with extended residual activity nor season long cultivation are necessary (104).

Numerous sorghum-weed competition relationships have been investigated in Nebraska. Burnside and Wicks (112, 113) stated that initial weed control should be initiated within 4 weeks after planting. In plots weeded 2, 3, 4, 5, 6 (about time of second cultivation), or 8 weeks after planting and kept weed-free thereafter, yields decreased 2, 5, 16, 24, 38, and 57% respectively. The major weed species were *Amaranthus hybridus* or *A. retroflexus*, *Setaria* spp. and *Digitaria sanguinalis*. Weeds grew slowly for the first 3 weeks, but rapidly thereafter; their dry matter production in the first 8 weeks also approached full season production.

Burnside and Wicks (114, 115) also discovered that weed competition had a greater effect on sorghum yield than crop row spacing of 51 or 102 cm, or crop plant populations of 27,000 and 46,000/A. The sorghum grown in 51 cm rows produced higher grain yields and lower weed yields. As weed competition increased, higher crop populations and narrower rows became increasingly more effective at suppressing weeds and reducing yield losses. Yield eased 4, 12, or 18% when weeding was delayed 3, 4, or 5 weeks compared to 2 weeks after planting. An identical row effect

was reported by Stickler and Anderson (493) who found 12.6% greater yields plus increased weed suppression in 20 inch rows compared to twice that. They related this to more tillering (heads/unit area) and larger heads in narrow rows. Burnside et al. (117) showed weed growth increased with row width, unless rows were cultivated. Weeds emerging more than 4 weeks after crop planting had no effect on yield (115).

Sorghum hybrids differ in their tolerance to weed competition (116, 476, 494). Hybrid comparative advantages largely derived from rapid germination and emergence, plus early root and shoot growth (214). Guneyli et al. (214) suggested plant breeders should give attention to these traits. The 16% yield reduction in plots hand weeded for 3 weeks after planting amounted to less than half the loss in plots cultivated once at 3 weeks after planting (35%). These data do not point to any advantage for continued early weeding, but rather to the advantage of weeding in the rows, a practice that can be accomplished manually.

Enyi (186) found that weeding 2 weeks after sowing in Tanzania surpassed weeding only at 4 or 8 weeks; the most effective method involved weeding at 2, 4, and 8 weeks, or slightly earlier than U.S. workers have reported. Weeding led to greater sorghum leaf area, ear length, and grain weight.

Small but consistent yield advantages for cultivation have been reported (111, 117). Two rotary hoeings increased yield even when weeds were removed weekly by hand (117). A combination of cultivation, narrow rows, and preemergence herbicides controlled weeds more effectively than any single method. Yield losses in these experiments averaged 1.12 kg of grain for each kg/ha of weed dry matter produced.

Glycine max—Soybean

Two reviews provide information on many aspects of weed control in soybeans (295, 542). Three other papers (20, 334, 335), plus a bulletin (21) from the state of Mississippi (in the U.S.), offer a comprehensive overview of *Xanthium pensylvanicum* control in soybeans. These studies and other sources indicate that weeds reduce the annual potential value of the U.S. soybean crop approximately 17%. This figure was taken from a 1960 U.S. Department of Agriculture report (522). A more recent survey tallied losses due to weed competition at 3.3 bu/A average yield reduction in 28 U.S. states, a 12% loss (23, 281). The study confirmed that weeds, when present at a known density throughout the growing season, will reduce yield by a predictable amount.

Several workers have studied variable plant population influence on competitive relationships. Generally, soybean stands with fewer than 9 to 11 plants/ft of row yield less and permit increased weed growth (551). Weed caused yield reductions increased more than tenfold when 9 to 15 soybean plants/ft of row were reduced to three plants. Probst (413) obtained opposite results; weed-free, uniformly planted soybeans produced equal yields when stand varied from 4 to 12 plants/ft of row. Another early study, by Weber, revealed that drilled, weed-free stands produced the same yield with six as with 16 plants/ft of row (549). Mixed annual grass and broadleaf weed populations offered greater competition for soybeans in 102 cm wide rows than in narrower spacing due to less early shading by the crop (108). Narrow rows increased yield partly due to shading, but also due to more optimal distribution of plants and greater efficiency in use of light, nutrients, and moisture.

Wax and Pendleton (543) encountered yield increases of 10, 18, and 20% for 76, 51, and 25 cm wide rows compared to 102 cm. Again, increases arose due to more rapid soil shading in narrower spacing (404). Rows 10, 20, 30, or 40 inches apart completely shaded the soil in 36, 47, 58, or 67 days (108). When herbicides were used, soybeans in 20 and 24 inch rows needed only one cultivation, but those in 32 or 40 inch rows always needed one or two cultivations to prevent losses due to weed competition (404). Shading effects at the sides of soybean rows produced greater yield reductions than top shading late in the season (123). Shading effects also may be less important when soil moisture becomes inoderately to severely limiting during mid-summer (123, 551). However, row spacing does not have significant influence on the number of weeds present at harvest (176). Row spacing does influence weed emergence. In 20 inch rows, weeds emerged for the first 6 weeks after planting compared to 7 weeks for 40 inch rows (118). Weeds yielded more consistently and soybeans less for 40 as opposed to 20 inch rows.

Detrimental competition does not always materialize when two or more species grow together (430). For example, soybeans sown in noncultivated 6 inch rows with winter wheat or rye as a companion crop developed yields equal to, or better than, soybeans grown without companion crops regardless of whether the crop grew under similar conditions or in cultivated 40 inch rows. The companion crop provided weed control in 6 inch, but not in 40 inch, rows. Other companion crops (*Vicia* spp., *Medicago sativa*, *Bromus inermis*, *Phleum pratense*, and *Trifolium pratense*) were more competitive and did not provide satisfactory weed control.

In Mississippi (U.S.), cultivation provided weed control superior to broadcast sowing with no cultivation (336). With heavy (undefined) weed populations, soybean plant densities of 80,000 to

200,000 plants/A did not increase yield with conventional, or cross cultivation, but did generate higher yields with broadcast sowing and no cultivation. As soybean populations increased from 39,200 to 78,000 to 156,200 plants/A, weed yields decreased from 900 to 570 to 470 lb/A, whereas crop yield increased from 1,930 to 2,150 to 2,200 lb/A (110). Weber et al. (550) studied the relationship of dry weight yield to leaf area index (LAI)^a and found high plant populations and narrow rows favored a high LAI. However, maximum soybean yield, when planted in narrow rows, occurred at less than the maximum plant population.

When soybean rows were kept weed-free approximately 1 month after planting, yields matched production from plots kept weed-free all season Wax and Slife (544) noted. Hammerton found weed control to be required for 6 weeks after emergence in Trinidad (224). Staniforth and Weber reported an average yield reduction of 3.7 bu/A (about 10%) when annual weeds were present for the entire season (490). *X. pensylvanicum* and *Cyperus esculentus* reduced yields 75% in the Southern U.S. (233). In the state of Iowa (U.S.) combinations of *Setaria viridis*, *Amaranthus retroflexus*, and *Chenopodium album* reduced soybean yield 74% (even when cultivated twice) compared to weed-free plots (488). However, with one rotary hoeing yield loss dropped to 34%. In one study *Setaria* spp. and *Polygonum persicaria* reduced yield about equally (551). In a second study *Setaria* spp. proved slightly less detrimental than *Polygonum convolvulus*, *Abutilon theophrasti*, or *A. retroflexus* (490).

Hinson and Hanson (253), Burnside (105, 106), and McWhorter and Hartwig (337, 338) reported differences in competitiveness of soybean cultivars. Staniforth (483) tested four cultivars with differing maturity dates; all four demonstrated equivalent responses to competition from annual weeds. Staniforth acknowledged that weeds benefitted more than soybeans from increased nitrogen fertilization and nitrogen residues from the previous year's corn crop fertilization. Two researchers (253) proposed photoperiodic response as the primary factor determining genotype relative competitive ability. Dowler and Parker found that the weed control system, specific year (especially those with precipitation in September and October), and variety all affected number and size of weeds at harvest (176). The highest harvest time weed population was always associated with high rainfall in September and October.

X. pensylvanicum ranks as the most important and detrimental weed in soybeans (71). Under drought conditions, densities of 2,000 to 64,000 weeds/ha reduced yield 15 to 100% (534). Yield reduc-

^aLAI = leaf area subtended/unit area of land

tions of 50% have been reported for 46,000 plants/ha (209). With 4,000, 8,000, 16,000, or 32,000 plants/ha yields slipped 20, 39, 63, and 78% (534). One *X. pensylvanicum* per 30.5 m of row reduced soybean dry matter production 59% and seed yield 87%. Total loss occurred with two weeds/30.5 m of row (534).

Barrentine (42) found yield reductions of 10, 28, 43, and 52% from *X. pensylvanicum* densities of 3,300, 6,600, 13,000, and 26,000 plants/ha, respectively, compared to weed-free plots. Soybeans effectively competed (without yield reduction) with less than 3,000 *X. pensylvanicum*/ha. Maximum yield without further control occurred when the weed was removed at 4 weeks. Ten weeks of competition reduced soybean height and 12 weeks reduced stand (42). *X. pensylvanicum* exerted half its yield reducing potential during the first 8 to 10 weeks after emergence and up to early flowering, and half during the period including late flowering, pod set, and early bean development. Barrentine's data (42) for yield reduction from 100,000 weeds/ha verify this observation. Yield lessened 10, 36, 40, 60, 80, and 90% for 4, 6, 8, 10, 12, and 16 weeks of competition after emergence. While *X. pensylvanicum* may decrease yields 50 to 90%, its presence definitely affects bean grade. Yield increased approximately 6% for each 10% increase in weed control. A 70% weed control level was required to avoid losses due to excessive seed moisture (20).

James et al. (275) measured several parameters of plant growth and found leaf area and dry weight were most affected by *X. pensylvanicum* competition. Within 30 cm of a *X. pensylvanicum* plant, leaf area at harvest shrank 19% and dry weight 15%. The effects lessened as the distance between crop and weed increased. Hence, seed yield slipped 0, 10, 25, and 47% due to weeds present 75 to 105, 45 to 75, 15 to 45, and 0 to 15 cm, respectively, from a soybean plant. A reduction in pods per plant (6, 11, 22, and 40% for the distances just mentioned) accounted for most of the yield losses (275).

Sorghum halepense, another strong competitor, reduced yield of six varieties 23 to 42% with hand or mechanical harvesting during a three year study. In the same study, *X. pensylvanicum* reduced yield 63 to 75% with hand harvest and 36 to 67% with mechanical harvest (393). Weed densities ranged from 7,400 to 15,000-16,500/ha. *X. pensylvanicum* competed for light more effectively than *S. halepense* (337). Competition losses attributed to *S. halepense* amounted to roughly half those from *X. pensylvanicum* (338).

A series of studies conducted in the state of Illinois (U.S.) by Knake and Slife (296, 297, 298, 299, 300) focused on *Setaria faberii*. Fifty four *S. faberii*/ft of row lowered soybean yield 28% (and corn 25%); 12/ft of row decreased yield 18%, and six plants

reduced it 10%. Competition damage, mainly fewer pods per plant with little effect on beans/pod or bean size (296), corroborated results from several other studies (178, 180, 352), but conflicted with work by Hammerton (224). Greatest losses occurred when soil moisture was adequate early in the season. *S. faberii* most actively competed when it began growing in the row with soybeans. Seeding the weed 3 weeks after the crop precluded its being able to produce seed and protected soybeans against yield loss. When seeded 3 weeks after corn, *S. faberii* produced 500 lb dry matter/A as well as seed, though no yield effect on the crop. Soybeans generate more early shade than corn establishing the former as more effective competitors (297, 298). Removing *S. faberii* when 3, 6, 9, or 12 inches high, and at maturity, reduced soybean yield 0, 0, 1, 2, and 18 bushels/A, respectively (299, 300). Competition sufficient to reduce yield began later in soybeans than in corn; weed presence during just the vegetative stage had no effect on yield. Yield reduction only resulted from competition during the crop's reproductive growth stage or when competition for light ensued (300). Corn became a more effective competitor late in the season because of its greater height.

Staniforth showed that *S. faberii* out competed *S. lutescens* and *S. viridis* because it grew more vigorously and produced greater amounts of dry matter (486). Yield reductions due to *Setaria* spp. competition were least when soil moisture was (480):

- a) adequate over the whole season;
- b) limiting over the whole season;
- c) limiting to the end of growth stage and then adequate to soybean maturity.

The results confirm water's importance to competitive effect. Greatest yield reductions occur when it is limiting during the reproductive period and, perhaps, when total soil moisture is at the extremes of limiting or adequate for the whole season. It is important to recognize that water can be limiting because it is not present (e.g., low rainfall) or due to weed competition.

In a representative study (42) one *Ipomoea purpurea* plant/30 cm of row reduced soybean yield 52% indicating a competitive ability nearly equal to *X. pennsylvanicum*. Maximum yield occurred when *I. purpurea* was removed no later than 4 weeks after soybean planting (557). Wilson and Cole (580) and Wilson (579) discovered that *I. purpurea* and *I. hederacea* competed equally well. Both reduced yield, height, and lodging and increased mechanical harvest difficulty. Yield sagged 12 or 44% at densities of one weed per 61 cm or 4 cm of row, respectively (580). Both require a 6 to 8 week period of control.

Oliver (378), Oliver et al. (379), and Scott and Oliver (452) studied several aspects of competition between *I. purpurea* and soybeans. Soybeans were competitive for 6 to 8 weeks after emergence. The weed became competitive 4 to 6 weeks after emergence when a rapid increase in its photosynthetic area occurred. As a result, the weed became three to four times more competitive during the soybean's reproductive stage than during its vegetative stage. At one weed/61, 30 or 15 cm of row, *I. purpurea* could remain for 10, 8, or 6 weeks, respectively, before yield loss occurred. Oliver et al. (379) proposed that crop-weed competition evaluation should include intraspecific and interspecific data. Reductions of leaf area index (LAI), dry weight, and crop growth rate (CGR)^a provided the most reliable indicators of when competition occurs during the growing season. LAI remained unaffected if *I. purpurea* was removed by 6 weeks after crop emergence. Competition for 8 weeks reduced LAI by 31%, but if weeded then, soybeans recovered rapidly narrowing difference from the check at 12 weeks to 4%. Full season competition reduced LAI 42% by 10 weeks and 31% at 12 weeks with one weed/61 cm of row. One weed every 15 cm negatively affected LAI by 6 weeks, and by 8 weeks soybeans were unable to maintain an LAI equivalent to an intraspecific competition plot. Full season competition at 15 cm spacing reduced LAI by 53% in 10 weeks and 60% in 12 weeks. CGR reflected the same general trend (379).

Other growth analysis parameters—height, growth stage, leaf-stem ratio, net assimilation rate, and relative growth rate—proved to be inadequate indicators (379). Root distribution and root development were both dynamic functions of growth stage, planting density, and species (452). The major volume of roots, as well as the greatest root length of crop and weed, developed in the upper 12 cm of soil, and near the row center. *I. purpurea* roots were found at greater depths and density than the crop's. The relationship may have arisen because the soybean roots increased relatively little after the crop's reproductive phase commenced and, at that time, *I. purpurea* was increasing at a rapid rate (452).

Abutilon theophrasti, according to Staniforth (486), demonstrated nearly double the competitiveness of *S. lutescens* or *S. viridis* on a yield reduction/cwt of mature weeds basis. Eaton et al., in a series of reports (179, 180, 181, 182), studied competition caused by *A. theophrasti* and two other *Malvaceae*: *Hibiscus trionum* and *Sida spinosa*. *A. theophrasti* proved most competitive producing 10 times more dry matter than the other weeds. Although their competitive ability varied, none of the weeds reduced yield when planted 20 to 40 days after soybeans (182). However,

^aCGR = average increase of plant material/unit of land/unit time

yields slipped one-third with simultaneous planting of weed and crop and one-fifth when weed seeds were planted 10 days later than soybeans. Yields survived 30 to 40 day competition from *H. trionum* unscathed, but dropped sharply under longer competition. Competition appeared to be enhanced by unfavorable rainfall distribution at critical growth periods. Competition varied between irrigated and dryland conditions; moisture was critical under dryland, whereas competition for light dominated under irrigation. One *H. trionum*/7.5 cm of soybean row reduced yield 632 kg/ha after 85 days. When the weed was banded between rows, yield contracted 270 to 651 kg/ha after 35 to 40 days competition. A natural stand of 215 weeds/m² reduced yield 454 kg/ha after 30 days and 1490 kg/ha after 110 days (181).

Amaranthus hybridus competition was studied in Illinois (352, 353). Forty weeds/m of row cut soybean yield 55% and only one plant/m of row reduced it 18%. In another study, one weed/ft of row (30 inch) reduced yield 25 to 30% (365). *A. hybridus* grew taller than the crop; the dry weight of crop plus weed amounted to nearly 1.3 times that of weed-free soybeans (352). Full season competition caused 65% yield loss primarily due to shading. In other experiments, total dry weight yield of soybeans and weeds were roughly equal (181, 490) or slightly greater (551). Natural stands of *Amaranthus* spp., observed Asberry and Harvey (33), could reduce yield up to 80% and produce 4 tons dw/A. Only one weed/8 feet of soybean row reduced yield 30% and produced ½ ton dw/A.

Berglund and Nalewaja (52, 53) found average yield reductions of 30, 36, 42, 50, and 51% after competition with 1, 2, 4, 8, and 16 *Brassica kaber* per foot of row at one location. At a second location, losses magnified to 62, 72, 80, 89, and 93% for the same densities. Each 100 lb dw of *B. kaber* reduced soybean yield 0.53 bu/A at the first location and 0.69 at the second. Removing the weeds 1, 2, or 3 weeks after soybean emergence blocked yield losses. Weeds left 7 weeks constricted yield 31% (52) to 60% (53). Longer competition did not cause further yield deterioration. Weeds sown 3 or 6 days prior to soybeans, reduced seed yield an average of 80% (53); when sown 3 or 6 days after soybeans, seed yield decreased only 5 to 7%.

Cassia obtusifolia depressed soybean yield linearly between zero and 15 weeds/m² (511). Yield was reduced 19 to 32% or 34 to 35% by 7.7 weeds/m² on sandy soils at two locations. Weeds removed no later than 4 weeks after soybean emergence failed to affect yield; also, no further weeding was required. Competition for as few as 4 weeks did reduce yield in some cases. Weed presence for 6 weeks reduced yield in two of five experiments, and competition for 8 weeks reduced yield in three of five

Anoda cristata was unable to compete effectively in soybean rows for periods up to 12 weeks and at densities up to 9.8/m of row, but did hurt yields in cotton (306).

Sorghum bicolor reduced soybean yield when 680 pounds of weed dry matter/A were produced. Plots maintained weed-free for 4 weeks after planting allowed soybeans to compete effectively (585).

Light to moderate (undefined) stands of *Cyperus esculentus* did not affect yield, though severe (undefined) infestations reduced yield 29% in the U.S. state of Minnesota (545). Another study in the same state (184) revealed corn as a better competitor with *Cirsium arvense* than soybeans. Corn primarily competed for water whereas light was more important in soybeans.

Park and Webb (390) detected a 3.5% soybean loss in a combine harvester because of weeds passing through the machine. Total harvest losses increased when harvesting *A. hybridus* infested soybeans as opposed to *S. faberii* (365, 366). Harvesting before weeds were desiccated by frost gave significant threshing and separating losses especially as forward speed increased from 1 to 3 mph (365). Stubble, lodging, and stalk losses increased two times in weedy plots after frost. In Nebraska, widely varying weed densities desiccated by frost did not reduce combine harvesting efficiency. Gathering losses averaged 16%, but threshing losses were less than 3% (118).

In another study, losses averaged over 3 years were: shattering 7.8%, stump (uncut pods low on stem) 1%, stalk (cut stems that fall to ground) 2%, and threshing 1.4%. Early harvest was slightly less detrimental than late (11 vs. 13.4%) (107). In actuality, worse combine losses occurred in weed-free plots than in weedy plots (grassy weeds had lower average losses than broadleaf species). Shattering and stalk losses increased in weed-free conditions. In weedy plots, extra weed bulk reduced total yield, but prevented excessive vibration of stalks during cutting and eliminated some losses (107).

Arachis hypogaea—Peanut, Groundnut

Peanut foliage not only grows slowly, but in a somewhat prostrate manner that does not rapidly cover the row, thus exposing the plant to competition for a majority of the growing season. The crop, to maintain yield, can tolerate only 10% weed ground-cover during the fourth to tenth week after emergence (178). Hill and Santelmann (250) found steady yield levels when weeds were removed within 3 weeks after planting and weed-free conditions

maintained thereafter. Four to eight weeks of competition with *Amaranthus hybridus* and *Digitaria sanguinalis* were required to reduce yields. Peanuts kept weed-free for six weeks after planting experienced no yield loss from weeds emerging later. Crops maintained free of *Cassia obtusifolia* and *Desmodium tortuosum* for 4 to 6 weeks remained free of these species all season and produced normal yields. Occasionally a brief 2 weed-free weeks produced near normal yields. Ten weeks of competition with these same weeds did lower yield (234, 235).

In similar studies, a single cultivation 4 weeks after emergence increased yields over uncultivated peanuts, but cultivation had no effect when peanuts were kept weed-free for 4 to 8 weeks (89, 91, 269), or 4 to 6 weeks (178). These data concur with earlier studies (101, 433 cited in 284, 382). However, Bhan et al. (54) reported that competition from *Cyperus* spp. and other weeds for 3 weeks significantly reduced peanut yield. Brown (82) indicated evidence of cultivar tolerance differences to weed competition. Buchanan and Hauser found that as peanut row width decreased from 80 to 40 to 20 cm, yield increased suggesting greater competitive ability in narrow rows (90).

Other workers have chronicled weed-caused peanut yield losses. Weeds reduced irrigated peanut yield by at least 50% in Libya (382) and up to 70% in Sudan (average loss in unweeded plots equalled 1490 kg/ha) (178). Two annual weeds lowered yield 44 to 48% in the U.S. state of Texas, whereas weeds growing only part of the season reduced yield 25%, part of which might have been due to the weeding operation (72). Hauser and Parham (236) reported an average yield loss of 20% in an eight year study primarily due to competition from *D. sanguinalis* and *Richardia scabra*. Losses ranged from one to 50%; however, no yield losses occurred in five of the eight years. Rawson (417) noted that *Ipomoea purpurea* weakened peanut yield 7.5% and one *Xanthium pungens*/9 ft² reduced yield approximately 16%. Another group (237) cited the similarity of *Xanthium pensylvanicum* to *X. pungens* and suggested an equal effect. Unpublished data (cited in 237) report that one *C. obtusifolia* or *D. tortuosum*/ft of row chopped yields in half and that one *D. sanguinalis*/3 ft of row, or one *Amaranthus retroflexus*/4 ft of row significantly reduced yield also.

Hill and Santelmann (250), in a two-year study, showed severe yield losses resulted when weeds competed for most of the season (Table VIII).

These data, as do all others, emphasize the importance of early weeding as well as the significant losses that weed competition can cause.

TABLE VIII

Peanut yield as influenced by length of weed-free period (250).

Treatment	Yield compared to weed-free treatment (%)	Yield loss (%)
Not weeded	5	95
Weeded for 2 weeks	12	88
Weeded for 3 weeks	28	72
Weeded for 4 weeks	39	61
Weeded after 6 weeks	46	54
Weeded after 7 weeks	32	68
Weeded after 8 weeks	17	83

Gossypium hirsutum—Cotton

Though a warm climate perennial, cotton behaves and is cultivated as an annual. Typically, growers plant cotton during a cool season. The crop's slow early growth permits early, vigorous weed competition. The data of Holstun et al. (260) emphasized the extent of weed growth; hoeing time for cotton in 1960 ranged from 14 to 53 hours/A. This figure paralleled Keeley and Thullen's estimate (291) of 26 to 44 hours/ha in 1975 when presumably more effective herbicidal weed control was achieved.

Several scientists have studied the influence different weeds exert on cotton. Plant growth parameters measured include: height, stem diameter, cotton quality factors, and yield. In all cases, yield has been the most sensitive indicator of weed competition. *Echinochloa crus-galli* can be a problem for irrigated cotton grown in the western United States (342). However, when the weed emerged after mid-June (the peak of summer for the cited region), it neither competed nor reduced crop yield, even when moisture and nutrients were adequate for weed growth. *Cyperus esculentus* competition at densities of 3 to 10 plants per three cotton plants in a greenhouse experiment was so severe increased water and nutrients could not overcome decreases in cotton dry weight yield (103). Competition from 1 to 3 *C. esculentus* per three cotton plants reduced cotton dry weight; but yield was reduced most when cotton was stressed by low fertility or low soil moisture. Seed cotton yield in hand weeded control plots averaged 14% higher than in plots where the weed remained throughout the season (288).

In a series of five field experiments, *C. esculentus* was hoed out of cotton at 0, 2, 4, 6, or 8 weeks after cotton emergence (291). Undisturbed *C. esculentus* increased from 23 plants/m of row at

emergence, to 100 at harvest. The number of shoots reached a maximum at 6 to 8 weeks. Competition with *C. esculentus* for over 4 weeks depressed yield. Competition for 6 to 8 weeks reduced yield 20% and full season competition cut it 34%. Competition had no effect on fiber properties, but did delay maturity, decrease height, and, in some instances, reduce stand. Weed removal at cotton emergence, followed by 14 weekly hoeings, thinned tuber population 24%. Removal 6 weeks after crop emergence followed by nine weekly hoeings resulted in a fourfold tuber production increase; however, without control, tuber number increased ten-fold. Keeley and Thullen (291) emphasized the importance of competition for light. *C. esculentus* averaged 11 cm high at cotton emergence and 44 cm eight weeks later. Height was equal to, or greater than, cotton during most of this period.

Xanthium pensylvanicum at densities of 1 to 10 plants per 10 cotton plants reduced cotton dry weight yield, but its effects were most severe under low fertility regardless of soil moisture differences (103). On a sandy loam soil, eight weeds/7.31 m of row reduced yield more than 20% and 48 reduced it more than 80% (87). *X. pensylvanicum*, while out-competing *Amaranthus retroflexus* on a sandy loam soil, only matched the latter on sandy clay loam. Crop yield on a sandy loam fell less than 50% due to 48 *A. retroflexus*/7.31 m of row; however, the same density in clay loam reduced yield 90%. Smith and Tseng found that *A. retroflexus* was the most detrimental of several *Amaranthus* species (468). At densities of one weed/0.30, 0.61, 1.22, or 2.44 m of row, lint yield dropped to 363, 321, 221, or 130 kg/ha compared with 666 kg/ha for weed-free cotton. They cited the ability of these species to compete for nitrogen as a major factor.

Buchanan and Burns studied *Cassia obtusifolia* and *Ipomoea purpurea* and found the latter slightly more competitive (86). Both species exhibited stronger competition on sandy clay than on sandy loam soil. Table IX compares the effects. Apparently *I. purpurea* was more competitive because of physically restricting cotton's normal growth. Neither weed affected percent lint or fiber properties. The high relative humidity in the cotton-*I. purpurea* canopy, however, caused more boll rot. The studies by Buchanan and Burns (86, 87) plus other work (83, 469) establish *X. pensylvanicum* as most competitive followed by *C. obtusifolia* and *I. purpurea* and finally *A. retroflexus*.

Sida spinosa grows taller than cotton and 2, 4, or 12 plants/ft of row reduced crop yield 27, 40, and 41%, respectively, compared to weed-free plots (271). Competition by 23 weeds/m² in an area 30 cm wide (centered on the cotton row) had no effect on yield (273). In one year, 43 weeds/m² stifled yield more than the 23 did, but 130 caused no further reduction. During the second year only 130/m²

caused a reduction; 23 and 43 weed plants were about equal, but affected cotton less than the control. Yield loss due to 130 *S. spinosa*/m² averaged about 39% annually over two years (272, 273). *Anoda cristata* reduced cotton leaf area/plant 31% at a density of 1.6/m and 57% at 9.8/m after 12 weeks competition (306).

TABLE IX

Comparative competitive ability of *Cassia obtusifolia* and *Ipomoea purpurea* in cotton on two soil types (86).

Weed and soil	Yield reduction	
	8 weeds/ 7.31 m row (%)	48 weeds/ 7.31 m row (%)
<i>Cassia obtusifolia</i>		
Sandy loam	10-23	45-65
Sandy clay loam	40	80
<i>Ipomoea purpurea</i>		
Sandy loam	10-40	70
Sandy clay loam	50-75	85

Studies, in addition to emphasizing yield losses due to weed competition, have focused on the period of severe competition and the optimum timing of weed control. For example, *S. spinosa* does not depress yield when removed no later than 5 or 6 weeks after cotton emergence (88). Martinez and Nieto reported that maximum spring cotton yield in Mexico required a weed-free period of 60 days after emergence and that no yield loss occurred if weeds were removed within 30 days of emergence (327). Winter cotton required 120 weed-free days after emergence, the increase being related to the winter variety's lower growing temperatures and consequent longer vegetative cycle (416).

These data contrast with results from Rhodesia reporting that yield ebbed when tall annuals, such as *Amaranthus hybridus* and *Nicandra physalodes*, grew past the 2 week postemergence point (508). Weeds emerging following hand cultivation at 4 to 8 weeks after crop emergence did not reduce cotton seed yield. Cotton attained 95-100% ground cover in 13 weeks, but the more voracious weeds reached the same level in 5 to 9 weeks. Therefore, competition centered on moisture which the weeds removed faster and to greater soil depths. Competition of *Digitaria sanguinalis*, *Eleusine indica*, and *Dactyloctenium aegyptium* reduced yield when the weeds were not removed for 6 to 8 weeks after emergence (84). Yields peaked when weeds were controlled for 7 to 9 weeks;

weeds emerging later did not affect yield. Cotton in 100 cm wide rows required approximately 8 weeks of postemergence weed-free maintenance to produce maximum yield (85) agreeing with data from Schwerzel and Thomas (451). Competition from mixed annuals for more than 6 weeks reduced yield. Weed control beyond 8 weeks, however, did not increase yield. Control could be delayed from 4 to 7 weeks (depending on location) before yield reduction became permanent.

Weeds allowed to compete after the crop's first or second irrigation (approximately 7 and 9 weeks after planting) reduced four year average cotton yield by 16 and 22% respectively (30), though no weed effect was detected in three of the study's four years. Yield was not affected if competition ceased after the first or second irrigation, or commenced after the third or fourth irrigation (approximately 11 and 13 weeks after planting). Early competition was negated in this study by planting cotton in moist soil under a dry soil mulch that hindered early germination of surface weeds; very few weeds (undefined) emerged before the first irrigation. Shaping seed beds also may control many smaller weeds. Competition from cotton itself thwarts weeds emerging after a fourth irrigation. Cotton planted 3 weeks later than *Cynodon dactylon*, *Sorghum halepense*, or *Cyperus rotundus* experienced severe growth reduction; at 10 weeks crop plants weighed only 15% of those growing without weeds. By contrast, cotton sown before the three perennials manifested only slight effects (261).

Unweeded cotton in the Sudan Gezira suffered 60% yield loss (178). The critical period occurred between 4 and 10 weeks after crop emergence. During this interval cotton could tolerate up to 25% weed ground cover without losing yield, though no definite relationship developed between yield loss and percent ground cover. Monocotyledonous weeds dominated; limiting their numbers during the crucial 6 weeks increased yield as much as 40%.

A contrasting study by Singh et al. (464) cited the need for a much shorter weed-free period. Control 15 days after crop emergence produced optimum growth and highest yield. Subsequent weeding delay, in 8-day increments, restricted crop growth and reduced yield by 8, 29, 30, 43, and 52% with control at 23, 31, 39, 47, and 55 days after emergence. Losses sustained during early competition were not recovered by removing weeds later in the season. One other study cited a relatively short 2 to 4 week weed-free requirement where *A. retroflexus* was dominant (431).

Buchanan and McLaughlin examined nitrogen fertilization's influence on weed competition and determined that, in two out of three years, supplementary nitrogen did not affect the weed-crop relationship (94, 95). In one year, cotton tolerated just 6 weeks of

competition, but managed 7 weeks when 67 or 100 kg/ha nitrogen were added. Six to eight weed-free weeks were required for maximum yield; apparently nitrogen played an insignificant role in the competitive relationship.

Treanor and Andrews (518) reported that cotton in an uncultivated control without herbicide yielded 108 kg/ha compared to 387 to 434 kg/ha when cultivated. Unpublished data (cited in 96) depict even greater advantage for eliminating competition by "as needed" cultivation (Table X). The primary effect of any type of cultivation is weed control and no additional benefits of cultivation were noted over hand weeding without soil stirring (92).

TABLE X

Yield response of weedy cotton to cultivation (86).

Cultivation	Mixed annuals, broadleaf, and grass weeds		Mixture of <i>Sida spinosa</i> , <i>Ipomoea purpurea</i> , and <i>Mollugo verticillata</i>		
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
			<i>kg/ha</i>		
As needed	2429	2438	2811	2404	2484
None	227	247	1024	861	801

Maximum yield occurred in 53 cm wide rows with as little as six weeks of weed-free maintenance (431). With 79 and 106 cm rows, ten and fourteen weeks were required. Row spacing became an important factor when weeds established themselves after cotton. The literature verifies no yield advantage for cotton in rows less than 106 cm apart.

Beta vulgaris—Sugarbeet

The world's sugar supply is derived roughly 40% from sugar beets and 60% from sugarcane. The two sugar crops rank as important commodities in world agriculture because of their multiplier effect and high income value to growers. Weed problems and control techniques associated with sugar crops differ due to variation in climatic requirements and growth habits.

Because the sugarbeet leaf canopy forms slowly, entire crops can be decimated by competition from certain weed species. Weeding must begin by the time sugarbeets have four to six true leaves yield can be depressed 120 to 150 kg/ha for each day weeds remain beyond this growth stage (454). Weeds need to be controlled until plants have 10 to 12 true leaves (454). Dawson (151) demonstrated a crop yield increase to a maximum matched by a decrease in weed

yield to zero for each additional week of weed-free conditions. The optimal point occurred between 9 and 12 weeks. Weeds that emerged early in the season, though most competitive, did not reduce sugarbeet root yield unless competing for 5 to 9 weeks after emergence (152). Yields held steady when weeds were controlled for 6 to 9 weeks after emergence. Another study (341) indicated that competition for less than 24 to 28 days left yield unaffected.

Burtch and Carlson (122) compared chemical and hand weeding and reported that uncontrolled *Echinochloa crus-galli* reduced sugarbeet root yields 2 to 14 T/A depending on the severity of infestation: a sparse infestation cut yields 10%, a moderate presence caused a 24% depression, and a dense population resulted in 43 to 90% loss. Weeds emerging after crop thinning still reduced root yield by 21 T/A compared to hoed weed control plots. Dawson (152) showed yield reductions of 49% for uncontrolled *E. crus-galli* and 94% for uncontrolled *Chenopodium album*. Mixed populations reduced yield 70%. Scott and Moisey (453) reported 80% yield reduction from full season competition from *C. album*. Other research has noted that broadleaf species—*Brassica* spp. (586), *Amaranthus retroflexus* (17, 80), *C. album* (454)—compete more vigorously than grassy weeds such as *Setaria* spp. (17, 80, 586), or other lower growing broadleaf species (454).

Several researchers have described specific weed densities impact on sugarbeet yield. Miller (341) reported that one-half, one, and two weeds/beet in the row reduced yield 6 to 11%, whereas four to eight weeds reduced yield 15%, all under non-irrigated conditions in the U.S. state of Michigan. Competition generated by two *Setaria viridis* in the beet row chopped yield as much as 80% (17, 80). Root yield fell 3.7 T/A (10.5%) when one *A. retroflexus*/8 ft of row competed all season. One *A. retroflexus*/sugarbeet reduced yield 70% compared to 26% for one *S. viridis*/sugarbeet. The same relationship held true when density doubled to two weeds/sugarbeet; two *A. retroflexus* dropped yield from 22.5 T/A (weed-free) to 4.3 T/A (81%) while two *S. viridis* reduced it to 14.4 T/A (36%). When *Brassica* spp. were restricted to a 10-inch band over the beet row, 20 plants/ft² were required to lessen yield below the weed-free check, but an equal density of *Setaria* spp. had no effect. The condition altered when weed plants grew between, as well as in, the crop row. As few as two *Brassica* spp./ft² depressed yield, being more detrimental than 20 *Setaria* spp./ft² (586). In California, Brickey (79) reported that one weed/six sugarbeets, or 17 weeds/100 ft of row, reduced root yield 2.9 T/A; one weed/3.3 plants, or 30 weeds/100 ft of row, reduced yield 4.8 T/A.

A series of papers (450, 546, 547, 548) focuses on competition between *Kochia scoparia* and sugarbeets. Yields dwindled when *K. scoparia* competed more than 5 or 6 weeks. Competition during the

entire season reduced yield more than 95%. Weed weight increased 59% when sugarbeets did not compete for the first 3 weeks, whereas sugarbeet reduced weed weight by 92% when *K. scoparia* was controlled for the first 4 weeks after crop emergence (546). Various weed densities negatively affected sugarbeet yield (548) shown in Table XI.

TABLE XI

Effect of *Kochia scoparia* on sugarbeet root yield (548).

Distance between weeds (ft)	Sugarbeet root yield ^a			
	1967 (T/A)	reduction (%)	1968 (T/A)	reduction (%)
1	5.0 f	76	5.0 f	79
2	8.9 e	59	8.1 e	67
5	13.7 d	37	13.7 d	44
10	17.1 c	21	18.0 c	26
25	19.8 b	8	20.9 b	14
no weeds	21.6 a	—	24.3 a	—

^aMeans followed by the same letter within a column were not significantly different at the 1% level as determined by Duncan's multiple range test.

One weed/25 ft of row reduced average root yield (over two years) by 2.6 T/A and sugar by 960 lb/A. *K. scoparia* exerted an influence within a 62 inch diameter circle. Based on earlier studies, Schweizer (450) developed a linear equation to predict how varying *K. scoparia* densities influenced root yield. The equation was most accurate ($\pm 5\%$) for weed densities of 20 plants or less/30.5 m of row. At greater densities, the quadratic or cubic equations were better predictors.

Arp (32) studied relative light intensity under the *K. scoparia*-sugarbeet canopy and found weeds spaced 2 ft or 25 ft apart caused reductions of 80 and 60%. Light constituted the principal limiting factor (174).

A full stand of sugarbeets (one plant/ft of row) will completely control late-emerging weeds. Weed growth in incomplete stands was roughly proportional to the unshaded area available (156). Dawson (151) described control by crop competition late in the season as "period II" and emphasized the absolute need for control by mechanical, chemical, or other means during the preceding stage, "period I." In a subsequent study (157), weed-free sugarbeets at 60 cm (50% stand) produced yields equivalent to those spaced 30 cm apart (full stand); a one-third stand—plants at 90 cm spacing—yielded 90% as much. These data emphasize the ability of sugar-

beets to compensate for poor stand. Though annual weeds emerging after the last cultivation succumbed to competition in a full stand, they exerted detrimental competitive effect in 50% or 33% stands compared to weed-free stands. Weeds, such as *Solanum sarachoides*, which did not grow taller than beets, had no effect on yield.

Saccharum officinarum—Sugarcane

Sugarcane, a perennial, tropical grass, thrives in warm, high moisture areas. Maturity in the U.S. ranges from 10 months in the state of Louisiana to 24 in the state of Hawaii. Orsenigo (383) emphasized that control practices should eliminate weed competition during crop establishment and minimize tall weeds and vines at harvest. While specific weed competition losses were not known as of 1970 (343), several studies have been conducted.

Because sugarcane is planted in widely spaced rows and grows slowly, it presents weeds an opportunity for early competition. Sugarcane in the West Indies requires weed control from the time primary shoots emerge to the first appearance of cane stalks between lowermost leaves (307) which makes the beginning of stalk elongation. The period extends from 3 to 12 weeks after planting. Because growth rates vary with geographic areas, plant growth stage is preferable to time after planting as a criterion. The West Indies experiment cited the perennial, *Paspalum fasciculatum*, as primary weed species. Weed growth beginning 12 weeks after crop planting left cane and sugar yields virtually unaffected. However, weed growth starting 3, 6, or 9 weeks after planting seriously reduced yield (Table XII). Delaying the first weeding until 9 weeks after planting reduced cane yield 21.5% and sugar yield 20%. Competition for three more weeks resulted in an additional 25% loss. Similar relationships, emphasizing the importance of early weeding, can be noted for instances where weeding ceased early in the season.

Arevalo et al. (27, 29) reported yield losses of only 8% when *Sorghum halepense* competed for the first 30 days after planting, but significant losses from competition for 60 to 90 days, and up to 70% loss from season-long competition. Competition began to cause yield reductions 60 days after cane emergence (28).

In Taiwan, weeding only during the second month after planting generated yields nearly as high as a weed-free plot (402). Hand weeding for 3 to 6 weeks produced the highest sugar yields compared to 13 weeks of hand weeding or herbicides.

TABLE XII

Competition between *Paspalum fasciculatum* and sugarcane (307).

Treatment	Yield reduction below weed-free control (%)
weed competition from planting to harvest	77.3
weed competition for 9 weeks after planting	21.5
weed competition for 12 weeks after planting	46.6
weed-free for 3 weeks after planting	77.6
weed-free for 6 weeks after planting	50.6
weed-free for 9 weeks after planting	41.7
weed-free for 12 weeks after planting	13.6—not significantly different from weed-free control

Sugarcane in Hawaii requires weed control for 4 to 5 months before the cane (in rows) closes over. However, *Cyperus rotundus* control was judged to be too expensive (252). Winter weeds, even though they grew for only "a few weeks" and were removed 8 months before harvest, reduced yields in Louisiana (343). Heavy *S. halepense* infestations in ratoon fields reduced yields 25 to 50% below a hand weeded check and often caused abandonment of the field after the first ratoon year (343). Ratoon cane heavily infested with *Digitaria* spp. required 125 man-hours/ha of weeding in mid-May, but 150 man-hours/ha 2 weeks later; the weeding delay caused a 20% decrease in sugar yields. Infestations of *Ipomoea hederacea* decreased yields 20 to 25% in India, largely from physical interference with plant growth and harvest (506).

Arevalo et al. (27, 29) reported no significant difference in the ability of five cane varieties to compete with *S. halepense* in a 5-year experiment in Argentina, though two varieties displayed superior competition tolerance. Mani and Gautman (320) reported yield losses of 12 to 54% in India, depending on sugarcane variety.

Vegetable Crops

At least one study has focused on each of the eleven vegetable crops to be discussed. Danielson's paper (146) on losses and costs due to weeds, while useful, does not offer much specific competition information. Roberts (423) summarized most of the British work treated individually herein.

Allium cepa—Onions

Onions exhibit greater susceptibility to weed competition than most other crops. Without weed control, onion yield shrinks nearly to zero. Because of onions' slow germination and early growth and the absence of dense foliage, initial competition tends to be severe (246, 422). Early weeding unfailingly produces highest yields. Weeds, even if present for only 2 weeks following crop emergence, can thwart crop growth (70, 561). Other studies have shown that the crop requires freedom from weeds for the first third of the growing season (388); or, that no reduction in yield occurred if weeds were removed 4 to 6 weeks after crop emergence (138, 244, 422) even when weed density was 80/ft² or 150/m².

Weeds primarily cause reduced bulb size, though they also depress photosynthetic capacity, leaf blade production, and number of leaves (244, 246, 459). No new leaves form after bulbing; the number and size of leaves present at that time determines eventual bulb size (422). Hewson and Roberts (246) reported that when weeds were removed 7.5 weeks after 50% crop emergence, minimal subsequent bulb dry weight or size increase occurred and only one or two small new leaves formed. Weed dry weight at 7.5 weeks ballooned to 20 times that of the crop. Weeds contained approximately one-half the available nitrogen and one-third the potassium. Observers suggested that initial competition centered on nitrogen, but that competition for moisture predominated later in the season.

Wicks et al. revealed that a combination of 54% *Amaranthus retroflexus*, 21% *Kochia scoparia*, and 25% annual grass weeds growing in a 16 cm band over the onion row for 2, 4, 6, or 8 weeks after onion emergence, reduced yield 20, 20, 40, and 65%, respectively (561). Plots weeded until onion emergence and for 2, 4, 5, 8, 10, or 12 weeks after emergence suffered yield losses of 100, 99, 87, 75, 46, 25, and 5%, respectively. To prevent yield loss, the researchers concluded, onions need to be kept weed-free for 12 weeks after emergence due to lack of vigorous crop foliage, and, as others have reported (422, 459), an inability to recover from competition.

Roberts (422) noted that competition began when weeds started to rapidly increase in dry weight, an important point. Beyond this point, onion yield decreased 4% for every day weeds remained. Thus, not only does the duration of weed presence influence competition, but also the behavior (i.e., growth rate) of weeds and crop during the competitive period.

***Beta vulgaris*—Table Beets**

Table (or red) beets require 2 to 4 weed-free weeks after 50% emergence to prevent yield losses (70, 245, 530). The presence of *Portulaca oleraceae* at 350 plants/m² for as short as a 14-day span after emergence reduced yield (529). In other studies, weed populations as high as 1300/m² did not constrict yield if removed by 4 weeks, postemergence. Beets differ from onions by dint of far greater recovery ability (245, 459); beets can recover completely from competitive weed pressure during the first 4 postemergence weeks (459). However, season-long competition can produce an 86% yield reduction (310). *Chenopodium album* at 32, 75, or 151 plants/m² cut beet yield 44, 89, or 97% (410). Yields decreased 45 to 98% from season-long competition by 15 to 250 weeds/m².

***Solanum tuberosum*—Potato**

In view of the fact that the white, or Irish, potato ranks as one of the world's most important (food) crops, surprisingly few weed competition data are available. The review article by Dallyn and Sweet (145) offers useful data on costs due to weeds, but little weed competition information.

Isleib (270), in the U.S. state of Michigan, reported that *Agropyron repens* reduced potato yield 52% below a weeded control or 70% when 40 lb/A of nitrogen were added. Mani and Gautman (320) reported yield reductions of 25 to 35% in India. Researchers have observed differing abilities among varieties to suppress annual broadleaf weeds (504, 583). Competitive ability directly correlates with early emergence, rapid early growth, and maintenance of a dense leaf canopy throughout the growing season (583); potatoes do not possess vigorous early competitiveness.

A study in Java found that while weeding took 20 to 30% of farmers' time, it accounted for only 2 to 6% of production costs. Zero weed control reduced yield 22% compared to weed-free plots. Potatoes kept weed-free for the first 4 weeks after planting experienced zero yield reduction (189). These results disagree slight-

ly with those of Saghir and Markoullis (440) who found a 58% yield reduction when weeds competed all season. A weed-free 3 week period after crop planting was insufficient to avoid yield loss. Full yield was obtained when plots were weeded for the entire 6 to 9 weeks after planting, or when weeds were removed at 6 or 9 weeks after planting. Thus, weed presence early in the season was not detrimental unless they were permitted to remain past the 6 to 9 week point after planting.

The paper by Bleasdale (69) describing the relationship between set characters and yield of potatoes is important to note when planning competition studies.

***Lycopersicon esculentum*—Tomato**

A series of three weed competition studies, all conducted in the U.S. state of New York by Mohammed and Sweet, examines the role of light (346), moisture and nutrients (348), and plant density (347) in competition with *Amaranthus retroflexus*. Thirty percent shade during the early growth phase reduced growth and yield of both crop and weed, though the latter was more sensitive than tomato. Similarly, close spacing had a greater effect on *A. retroflexus* than tomato (346, 347). A four-year study revealed that *A. retroflexus* grown in densities between 16 and more than 200/4 m² produced similar fresh and dry weights/unit area, whereas five weeds/4 m² produced only one-half to two-thirds of maximum. Tomato densities of 16, 64, and 256/4 m² produced similar fresh and dry weights/unit area. One weed/3 m of tomato row caused almost 30% yield reduction and six plants/3 m accelerated the loss (347). Below ground competition primarily focused on water. In nutrient culture experiments tomato weights were only slightly reduced at a nutrient level 25% below normal. If tomato and *A. retroflexus* were grown together in nutrient culture, tomato weights were reduced 50% (349).

***Brassica oleracea capitata*—Cabbage**

Competition from *Stellaria media* not only affected internal head quality and number of plants producing heads, it caused some crop plants to die (311). As few as three *Chenopodium album*/m² reduced yield pointing to a linear relationship between yield and density of *C. album* (243). Thus, both *S. media*, a low growing but early emerging weed, and *C. album*, which emerged with the crop but grew above it, provided severe competition. Contrary to Hew-

son's linear relationship (243), Roberts and Bond (424) found no relationship between yield reduction and either weed fresh weight at harvest, or initial weed density. In one experiment 300 *C. album* plants/m² caused a 9% yield reduction, but in a second study 97 weeds/m² cut yield 75%. When *S. media* dominated, a similar lack of correlation appeared; 150 weeds/m² reduced yield 25% in one test, whereas 86 weeds/m² caused a 46% drop in another trial.

The lack of relationship between yield reduction and initial weed density, or harvest weight, gained confirmation in another work (425). Natural weed populations of 50 to 540 plants/m² reduced yield 47 to 100% compared to a weed-free control. When weeds were removed more than 3 weeks after 50% crop emergence and the crop was then kept weed-free, undiminished yield occurred. If the crop was kept weed-free for the first 2 weeks weeds established later did not reduce yield. The research team concluded that no critical weed competition period existed, and that a single weeding 3 weeks after half the crop had emerged produced yields similar to plots maintained weed-free all season (425).

Brassica oleracea botrytis—Broccoli

California growers produce broccoli year-round. Weed competition delayed maturity in winter planted broccoli with a 125-day growing season, but not in the 90-day crop. Yields contracted 30 to 40% due to annual broadleaf weeds competing for more than 30 days (2).

Phaseolus vulgaris and Vicia faba—Beans

Weed competition-caused yield loss may exceed the usual 20% if tall weeds are present (423). Beans tolerate weed competition more successfully than other vegetables because of rapid emergence and a shorter growing season (247). In a British study, natural annual weed stands of 104 and 580 plants/m² reduced yields 13 and 27% in spring-sown broad beans (247). During a year with water stress, 400 weeds/m² chopped yield 80%. Removing weeds 4 weeks after 50% emergence followed by weed-free conditions generated yield equal to plots weeded all season. Weeds developing 1 to 1.5 weeks after emergence had no effect on yield. A weed competition critical period did not occur, concluded the investigators, and a single weeding at 3 weeks would suffice (247).

The foregoing results do not agree with those of Dawson (150) who studied competition in irrigated field beans. When either *C. album* or *Echinochloa crus-galli* was controlled for the first 5 to 7 weeks after emergence, yield was not affected. *E. crus-galli* only reduced yield when it competed for more than 8 weeks. Weeds emerging soon after crop planting caused the greatest yield reductions, but only when they competed for several weeks. Yield did not fall until weeds grew taller than beans and competed for light. The need for weeding during the first third of the crop's life was confirmed in other studies (4, 41, 66, 533), all cited by William and Warren (572). William also reported an 81% yield loss from *Cyperus rotundus* competition when beans were irrigated once (570). Glasgow et al. (204) found the period from 3 to 5 weeks after emergence of *V. faba* to be a critical phase in one study, but not in a second; yield slipped 46 to 48% during two years of experimentation. In England, competition from *Agropyron repens* depressed bean yield 79%.

Pisum sativum—Peas

Nelson and Nylund (367) found that three *Brassica hirta*/ft² caused a yield loss equal to 27 *Setaria* spp. Competition occurred primarily for light and moisture. *B. hirta* emerging 3 days before peas lowered fresh weight of pea vines 54%, but only 17% when it emerged 4 days after peas (367). Full-season competition from three *B. hirta*/ft² reduced yields 0 to 64% during a 3 year span. Results varied with weed population, duration of competition, relative time of pea and weed emergence, and seasonal rainfall. *Agropyron repens* affected growth and yield, but only at dense planting levels (954 kg rhizomes/ha). Pea and vine yields were reduced and maturity accelerated (414).

Cucurbita spp.—Squash

Weed-free squash plots produced the highest yields during a New York study (495). A vine-type cultivar competed well with *Amaranthus retroflexus* and *Chenopodium album* when planted early, but not when planted late. Bush and semi-bush cultivars competed effectively with *Cyperus esculentus* when planted late, but the vine-type did not. While yields in weed-free plots were not affected by planting date, early planting proved superior for all weedy plots.

Lactuca sativa—Lettuce

Natural infestation of 65 to 315 weeds/m² caused complete, or nearly complete, loss of yield (426). When weeds were removed no later than 3 weeks after 50% crop emergence, followed by regular weeding, yield matched production from plots kept weed-free all season. Conversely, weed development after 3 weeks did not affect yield leading the authors to conclude that no critical weed competition period existed. Initially weeds reduced the number of marketable heads with firm hearts; more severe competition depressed marketable weight and often caused total crop loss. Effects appeared at 0.3 weed/m². Densities greater than 60/m² precipitated total loss. Plants primarily competed for light as evidenced by stem elongation, chlorosis, and reduced leaf production.

Daucus carota sativa—Carrot

Carrots possess capability to recover from competition when weeds are removed early; however, yields can shrink 30 to 60% under severe competition (459). The critical period develops during the first third of the growing season (65).

William (571) and William and Warren (572) studied competition between *Cyperus esculentus* and seven vegetable crops in Brazil. *C. esculentus* competed primarily for water and nutrients. Weed presence throughout the season severely impaired yields of carrots and other vegetable crops:

	<u>% yield loss from full-season weed competition</u>
transplanted tomatoes	53
transplanted cabbage	35
cucumbers	43
bush beans	41
okra (<i>Hibiscus esculentus</i>)	62
carrots (2 cultivars)	39 and 50
garlic (<i>Allium sativum</i>)	89

Transplanted tomatoes and cabbage could be weeded once, 4 weeks after transplanting, without incurring extensive loss from weed competition. Weeding once at the 4 week point also proved satisfactory for fast growing crops such as cucumbers (*Cucumis sativus*) and beans. For the very competitive cabbage and carrot crops, a first weeding often could be delayed until 5 to 7 weeks after planting. However, slow-growing okra, one carrot cultivar,

and garlic required two or more weedings at 3 and 6 weeks after planting; the first weeding was most important.

Pastures and Legumes

The bulk of competition research concerning these crops, predominantly conducted in Australia, has emphasized the interrelationship of light, nutrients, and water. Intraspecific competition among annual pasture plants increased with density, stage of growth, and decreased nutrient status (167). With adequate water and nutrients, total dry matter yield/unit area did not decrease, even in very dense populations. In later studies, Donald (168) showed that maximum dry matter production of *Trifolium subterraneum* and *Lolium rigidum* var. *Wimmora* occurred at moderate densities (approx. 10 to 16 plants/ft²) and was maintained at all higher densities (up to 750 to 920 plants/ft²). Black demonstrated the importance of large seed size as a determinant of success (58).

Fertility and species interacted in grass-clover swards; increasing nitrogen fertilization spurred grass yield, thereby producing greater grass leaf areas above the clover leaf canopy (492). The grass leaves diffused light intensity reaching clover plants leading to reduced clover growth. Work by de Wit (165) confirmed the result by disclosing that nitrogen fertilization stimulated *Glycine javanica* when mixed with *Panicum maximum*. Stimulation of either grass or legume density, or elimination of gaps in a pasture, reduced the weight of weeds (219). Peters (403) showed that pasture weeds could be controlled by increasing forage competition. In fact, crop growth rate stands as the single best measure of plant response to weed competition in forages (449). Growth rate and yield of timothy were increased by control of *Solidago nemoralis*. Yield increased 0.8 to 1.0 lb for each 1 lb of weeds that failed to grow (405).

Addition of phosphorus and potassium increased the growth of two clover species and *Lespedeza* spp. Nitrogen supplied by legumes enhanced growth of grasses and the net effect was weed growth reduction. High rates of nitrogen increased grass growth in competition with *Cirsium arvense* and three other forage species, according to work by Thrasher et al. (510).

Cords (142) found an inverse relationship between weed and alfalfa protein content. Irrigation favored *C. arvense* mainly during the year of alfalfa stand establishment, but, over a 2-year span, the weed declined more rapidly in irrigated plots. *Festuca arun-*

dinacea was most, and *Poa pratensis* (Kentucky bluegrass) least, competitive with *C. arvensis*. *Trifolium repens* (white clover) out-competed trefoil (*Lotus corniculatus*) in full stands. Thrasher et al. (510) found competitive ability (amongst forage species as well as against weeds) to be important early in a forage stand's life, but, with increasing age, the effect of cutting eclipsed competitive ability.

Light and moisture are critical to establishment of *T. repens* var. *ladino* in *Dactylis glomerata* (orchardgrass) sod (569). *Ladino* dry matter production diminished mainly due to root competition for moisture, notwithstanding Donald's (171) thesis that light, because it cannot be accumulated or stored, ranks as the primary limiting factor in forage production.

Broadleaf weeds suppressed development of legumes more than annual grass weeds did (257). Controlling broadleaf species released annual grasses which, in turn, caused less legume yield loss. Total weed yields in unrestricted stands were 3.5 to 5 T/A, but one hand weeding reduced weed yield to 1 T/A or less. Alfalfa and *Chondrilla juncea* mainly competed for moisture. When an annual *Medicago* challenged the same weed, light became the limiting element (556). Alfalfa, a perennial, successfully suppressed *C. juncea*.

Mather (328) reported that *C. arvensis* could be eradicated readily and economically by seeding infested land to forage crops, alfalfa being particularly effective. Schreiber (446) showed that, regardless of initial density, all alfalfa stands without control approached one *C. arvensis*/ft² after four years. Mowing after grazing eliminated *C. arvensis* and increased production 6.2 T/A compared to no control. Two *C. arvensis*/ft² reduced alfalfa production 7.4 T/A over a 4-year span measured against weed-free conditions. The same density reduced forage consumed by 4.7 T/A. Consumption was reduced because of the competitive vigor of *C. arvensis*, not because of dietary preference or palatability of the crop.

For alfalfa or *Digitaria sanguinalis* grown in nutrient solutions, either alone or together, dry matter production and percentages of phosphorus and potassium in plant tissue remained more constant for alfalfa (290). In association, *D. sanguinalis* increased independently of the crop when phosphorus and potassium levels remained high or when potassium was low. The weed's competitiveness probably developed from its rapid growth rate rather than nutrient uptake efficiency. Field studies, however, contradicted these data; *D. sanguinalis* demonstrated great competitive ability against trefoil, but not against alfalfa (447). In alfalfa, *C. album* proved more competitive than *Amaranthus retroflexus*

which out-competed *Setaria faberii* (447). The same relationship existed in the seedling stage (448). *A. retroflexus* caused far more damage to yield than *S. faberii* (Table XIII). *Lychnis alba* competed less aggressively after the first alfalfa cutting (398).

TABLE XIII

Competition of *Amaranthus retroflexus* and *Setaria faberii* with alfalfa (448).

Competition	Yield	
	Two cuttings in year of establishment (kg/ha)	Three cuttings first year after establishment (kg/ha)
alfalfa alone	5690	12,700
alfalfa and <i>Setaria faberii</i>	1165	10,400
alfalfa and <i>Amaranthus retroflexus</i>	200	3,800

Companion crops significantly reduced stand and yield of trefoil with, and without, herbicides (444). As part of their forage studies, Schreiber and Oliver (449) investigated weed competition with trefoil. Alone, the crop yielded 5256 kg/ha, whereas in competition with *S. faberii* or *A. retroflexus* yields crumpled to 935 and 125 kg/ha, respectively (449).

Other Crops

For a number of other crops, relatively few competition studies have been performed and there is a lack of specific knowledge of the effects of weed competition.

Orchards

Orchard weed control has relied on clean cultivation or use of low growing perennial grasses. The former, while effective, incurs high costs and offers opportunities for wind and water erosion. Perennial grasses, which require mowing, compete for nutrients and water (497), though they provide erosion control and may mobilize soil nutrients such as phosphorus and potassium (497).

Grass cover restricts apple tree (*Malus* spp.) growth and yield mainly due to competition for nitrogen (73, 208, 432). In southeastern England however, competition for water predominated (559). Atkinson and Holloway reported that competition from annuals

such as *Capsella bursa-pastoris* and *Senecio vulgaris* did not reduce total shoot growth, but did reduce yield in light crop years and fruit size in light and heavy crop years (36). Weed competition also accentuated the tendency toward biennial bearing.

Young trees in weed-free soil responded to supplementary nitrogen though often harmed by it (208). However, with sod present, the trees' best growth occurred with nitrogen fertilization.

In greenhouse experiments, two perennial grasses and one sedge caused severe growth reductions of sour orange trees (*Citrus aurantium*) by competing for nutrients and water (262).

Rubus idaeus—Raspberries, and *Fragaria chiloensis*—Strawberries

If weeds germinating in raspberries following planting in late March were removed by early June, they had no effect on the number of new canes produced. Dense weed growth during June and July reduced cane growth and caused mortality. Fruit yields and new cane production ebbed in the second year in previously weedy plots (313).

In a similar study focused on strawberries, Lawson and Wiseman (314) showed that crop growth was not affected by annual weeds germinating after planting (in late March) if removed by late May. Dense weed cover thereafter either severely limited stolon growth, or if remaining beyond mid-August, eliminated it completely. Weeds appearing after mid-June had no effect. Weeds left untouched until early September had less effect on berry production than unrestricted stolon growth did. Thus, interplant competition was just as detrimental to yield as intraplant competition. Stolon, or runner, production suffered most from weeds. Plant survival was unaffected.

Brassica oleracea var. *acephala*—Kale

Greenhouse studies by Hammerton concerning competition between three weed species of the genus *Polygonum* and kale revealed that *P. lapathifolium* was most and *P. aviculare* least competitive with *P. persicaria* intermediate (222). *P. lapathifolium* and *P. persicaria* produced more dry matter and showed a greater inverse response to the number of kale or weed plants per pot. Williams (577), in a second greenhouse study, demonstrated heavy kale mortality when *Chenopodium album* had an initial growth

advantage. When kale grew first, *C. album* remained stunted, but completed its life cycle. Williams related this characteristic to *C. album*'s plasticity. The lower leaves of *C. album* failed to form though an increased number of smaller, upper leaves did, as well as reduced branching. However, the weed still grew rapidly, trapped light, and set seed.

Another study by Hammerton (223) evaluated field growth of kale in competition with *Sinapis arvensis*, *Stellaria media*, *C. album*, and *Poa annua*. If any one of the first three weeds occurred abundantly early in the crop's growth, immediate and thorough weed control became essential. One hoeing sufficed for a sparse stand of *S. media* or *P. annua*; densities greater than 100/yard² required more intensive control. *P. annua* as the major weed required little or no control even when density exceeded 100/yard² 30 days after sowing.

Helianthus annuus—Sunflowers

Maximum sunflower yield occurred under 4 to 6 weeks of postplanting weed-free conditions (280). Weeds removed earlier than 4 weeks after planting did not influence head or seed size; weeds left longer than 6 weeks decreased both. Weeds that emerged after a cultivation at 2 weeks, and allowed to grow all season, resulted in a sunflower crop with the smallest heads and seeds of the various test plots. The density factor did not seem to affect flowering or maturity date.

Miscellaneous

Dew and Keys formulated an equation to estimate the loss of yield due to competition of *Avena fatua* in rape (*Brassica campestris* L.) (162).

Narcissus bulb yield decreased 4 to 21% due to annual weed competition (312).

Fretz (198) showed that container grown Japanese holly (*Ilex crenata*) was very sensitive to competition from either *A. retroflexus* or *D. sanguinalis*. Densities of 1, 2, 4, 8, 16, or 32 weeds/2.4 or 6 liter container all reduced yields by more than 30%; one weed was as destructive as 32. The effect moderated in the larger containers.

Another study indicated that 624 man hours were required for weeding one acre of nursery stock grown in 2.4 liter containers (385).

Alopecurus myosuroides sown 3 weeks after seeding of perennial grass seed crops competed more vigorously than when sown

10 weeks after crop seeding, even if sown at a higher rate. Crops withstood competition in the descending order of perennial ryegrass, timothy, orchard grass, Italian ryegrass, and last, meadow fescue (98).

The limited information available concerning weed competition in tropical plantation crops (421), citrus (282), and deciduous fruit and nut crops (309) appears in the **Proceedings of the International Conference on Weed Control** held at Davis, California, USA, in 1970.

Aquatic

Timmons (517) has pointed out that aquatic and ditchbank weeds cause indirect losses as a result of: reduced flow to cropland; water loss by seepage, evaporation, and plant transpiration; and, reduced drainage from cropland.

In other articles, Timmons (515, 516) reviewed the major aquatic weed problems, their extent and control. Early reviews were cited including one by Holm et al. (259) which emphasized tropical aquatic weeds.

Clearly the same criteria for assessing weed competition cannot be employed in the aquatic, as opposed to the terrestrial, environment. There are no known appraisals of direct crop losses due to aquatic weeds. However, limited existing aquatic weed competition information coincides with Timmons' (517) three points. Timmons (515) stated that, "man-made lakes above dams across major rivers in Africa, Asia, and Central and South America have become so badly infested with weeds within 5 to 10 years (after construction) that their usefulness for power development, boat transportation, and irrigation have been greatly reduced." Aquatic weeds quickly reduced the designed flow of some irrigation canals in India by 40 to 50% and others up to 80% (215). Submerged weeds retard water flow up to 20 times, whereas floating weeds only retard it two times (216). Decreases in flow reduce the possibility of irrigating distant fields, while accelerating the opportunities for leakage and evaporation.

Indian studies (78) documented evapotranspiration losses from six emerged and floating weeds. While no increase was noted for three species, evapotranspiration of *Eichhornia crassipes* was 30 to 40% higher, *Typha augustifolia* 60 to 70% higher, and *Cyperus rotundus* 130 to 150% higher than that from a free water surface. Metha (cited in 216) estimated that a hectare of *Typha* spp. transpired 80 million L of water/year which would have irrigated 4.6 ha of rice, or 11.7 ha of wheat. □

VI. The Effect of Competition Duration

Growers often assume erroneously that removing weed competition any time during the growing season solves the problem. However, substantial evidence indicates that time of removal is as important as removal itself. A justifiable assumption that the earlier weeds are removed, the better, may be true because of pragmatic reasons such as convenience, combination with other operations, or preparation for irrigation. Conversely, the assumption may prove false if crop growth and ultimate yield are the operative criteria. Unquestionably, the longer weeds compete after crop emergence, the greater their effect may be. However, no effect of any magnitude occurs (exclusive of the allelopathy phenomenon) until competition begins at the point when environmental resources (principally water, nutrients, and light) cease meeting the needs of two or more plants in an area (140). Therefore, weed presence cannot automatically be judged damaging and in need of immediate control.

The literature reviewed frequently refers to the duration of weed competition often called the critical period. Generally, the phrase "critical period" defines the maximum period weeds can be tolerated without affecting final crop yields or the point, after which, weed growth does not affect final yield. Most of these citations have been compiled in Tables XIV and XV. Some were assembled previously by Dawson (154, 155). The data for a particular crop exhibit consistency when more than one report was available. Variations in the length of required weed-free or "critical period" usually relate to differences in competing weeds or geographic region.

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TABLE XIV

Early weed competition duration tolerated without yield loss by crops.

Crop	Length of competition tolerated after		Competing weeds	Location	Source
	Seeding	Emergence			
—— (weeks) ——					
bean	8		<i>Echinochloa crus-galli</i>	Washington, USA	150
bean		3 to 5 after 50% emerg.	mixed annuals	England	204
bean	3		mixed annuals	Chapingo, Mexico	371
bean		4	<i>Amaranthus retroflexus</i>	Oregon, USA	573
green bean	4		<i>Cyperus rotundus</i>	Brazil	572
broad bean		4 after 50% emerg.	mixed annuals	England	247
beets, red		4 after 50% emerg.	mixed annuals	England	245
cabbage		3 to 4	mixed annuals	England	426
cabbage		4	<i>Cyperus rotundus</i>	Brazil	572
carrot		5	<i>Amaranthus retroflexus</i> <i>Acnida sp.</i> <i>Polygonum persicaria</i>	Wisconsin, USA	459
carrot	3 var. Kuroda; 5 to 7 var. Nantes		<i>Cyperus rotundus</i>	Brazil	572
corn	3		mixed annuals	Veracruz, Mexico	369, 370
corn		4	mixed annuals	Mexico City	7
corn	4		mixed annuals	Chapingo, Mexico	371
corn	2 to 4		<i>Atriplex patula</i> <i>Veronica persica</i>	England	102
corn	4		<i>Setaria viridis</i>	Ontario, Canada	463
corn	6		<i>Setaria faberii</i>	Illinois, USA	300

Crop	Length of competition tolerated after		Competing weeds	Location	Source
	Seeding	Emergence			
		— (weeks) —			
corn		6	<i>Amaranthus retroflexus</i>	Oregon, USA	573
corn		2 to 3	mixed annuals	New Jersey, USA	316
corn		8	<i>Rottboellia exaltata</i>	Rhodesia	507
cotton, Winter		17	mixed annuals	Sinaloa, Mexico	416
cotton, Spring		9	mixed annuals	Sonora, Mexico	327
cotton		8	mixed annuals	Alabama, USA	85
cotton	2		mixed annuals	India	464
cotton		2	<i>Amaranthus hybridus</i> <i>Nicandra physalodes</i>	Rhodesia	508
cotton	9		mixed annuals	Arizona, USA	30
cotton		6	<i>Sida spinosa</i>	Alabama, USA	88
cotton		4	<i>Cyperus esculentus</i>	California, USA	291
cucumber	5		<i>Cyperus rotundus</i>	Brazil	572
flax		2	<i>Avena fatua</i>	N. Dakota, USA	51
flax		2	<i>Avena fatua</i>	Manitoba, Can.	74
garlic	3		<i>Cyperus rotundus</i>	Brazil	572
lettuce		3 after 50% emerg.	mixed annuals	England	424
oats	1		mixed annuals	New Jersey, USA	316
okra	3		<i>Cyperus rotundus</i>	Brazil	572
onion		4 after 50% emerg.	mixed annuals	England	422
onion		4 after 50% emerg.	mixed annuals	England	246

Crop	Length of competition tolerated after		Competing weeds	Location	Source
	Seedling	Emergence			
	—(weeks)—				
onion		5	<i>Amaranthus retroflexus</i> <i>Acnida</i> sp. <i>Polygonum persicaria</i>	Wisconsin, USA	459
onion		12	<i>Amaranthus retroflexus</i> <i>Kochia scoparia</i> annual grasses	Nebraska, USA	561
peanut	6		<i>Amaranthus hybridus</i> <i>Digitaria sanguinalis</i>	Oklahoma, USA	250
peanut		4 to 6	<i>Cassia obtusifolia</i> <i>Desmodium tortuosum</i>	Alabama, USA	235
peanut		4	<i>Cassia obtusifolia</i> <i>Desmodium tortuosum</i>	Alabama, USA	91
potato	4		<i>Eleusine indica</i> <i>Panicum repens</i> <i>Galinsoga parviflora</i> <i>Polygonum nepalense</i>	Java, Indonesia	189
potato	6		<i>Amaranthus retroflexus</i> <i>Chenopodium album</i>	Lebanon	440
potato, sweet	3		unknown	West Indies	285
rice, paddy		3	<i>Echinochloa crus-galli</i>	Arkansas, USA	471
	7 to 9		<i>Echinochloa crus-galli</i>	Arkansas, USA	473
		4	<i>Heteranthera limosa</i> <i>Sesbania exaltata</i>	Arkansas, USA	471

Crop	Length of competition tolerated after		Competing weeds	Location	Source
	Seedling	Emergence			
		— (weeks) —			
rice, paddy	6		<i>Cyperus difformis</i>	New South Wales, Australia	500
rice, paddy	3 after transplanting		<i>Echinochloa crus-galli</i>	Philippines	319
rice, paddy	4 after transplanting		<i>Echinochloa crus-galli</i>	Philippines	373
rice, upland		8	mixed annuals	Korea	391
rice, upland		6	mixed annuals	Philippines	525
sorghum	4		mixed annuals	Nebraska, USA	113
sorghum	4		<i>Amaranthus</i> spp.	Texas, USA	524
sorghum		6	<i>Acnida altissima</i>	Kansas, USA	192
soybean	7		<i>Ipomoea hederacea</i>	Delaware, USA	580
soybean	4		mixed annuals	Illinois, USA	544
soybean	8 to 9		<i>Setaria faberii</i>	Illinois, USA	300
soybean		4 to 8 dependent upon spacing	<i>Ipomoea purpurea</i>	Arkansas, USA	379
soybean		2 to 4	<i>Cassia obtusifolia</i>	Alabama, USA	511
soybean		6	<i>Hibiscus trionum</i>	Kansas, USA	181
soybean		3	<i>Brassica</i> spp.	N. Dakota, USA	53
soybean		2 to 4	<i>Cassia obtusifolia</i>	Alabama, USA	97
sugarbeet	12		<i>Echinochloa crus-galli</i>	Washington, USA	152
sugarbeet		4	<i>Kochia scoparia</i>	Colorado, USA	546
sugarcane	4		<i>Sorghum halepense</i>	Argentina	27
sugarcane	8		mixed annuals	Argentina	28
sunflower	4		mixed annuals	Georgia, USA	280

The effect of competition duration

Crop	Length of competition tolerated after		Competing weeds	Location	Source
	Seedling	Emergence			
	—— (weeks) ——				
tomato	3 after transplant		<i>Cyperus rotundus</i>	Brazil	572
tomato	4 after transplant		unknown	West Indies	285
wheat, spring		2	<i>Avena fatua</i>	Manitoba, Canada	74
wheat, spring		4 to 5	<i>Avena fatua</i>	England	132
wheat, winter	~22 (Oct.→ Mar.)		<i>Bromus tectorum</i>	Oregon, USA	436
yams	12		unknown	West Indies	285

TABLE XV

Weed-free period required to prevent crop yield reduction.

Crop	Weed-free period required after		Competing weeds	Location	Source
	Seeding	Emergence			
	— (weeks) —				
bean	5		mixed annuals	Washington, USA	150
bean, broad		1 to 1.5 after 50% emerg.	mixed annuals	England	247
bean, dwarf		1 to 1.5	unknown	West Indies	285
beet, red		2 to 4	mixed annuals	England	245
cabbage		2	mixed annuals	England	426
corn		9	mixed annuals	Mexico City	7
corn	5		mixed annuals	Veracruz, Mexico	369, 370
corn	3		<i>Setaria faberii</i>	Illinois, USA	298
cotton		6	mixed annuals	Alabama, USA	85
cotton, spring		4	mixed annuals	Sonora, Mexico	327
lettuce		3 after 50% emerg.	mixed annuals	England	424
peanut	3		<i>Amaranthus hybridus</i> <i>Digitaria sanguinalis</i>	Oklahoma, USA	250
peanut		10	<i>Cassia obtusifolia</i> <i>Desmodium tortuosum</i>	Alabama, USA	235
peanut		8	<i>Cassia obtusifolia</i> <i>Desmodium tortuosum</i>	Alabama, USA	91
potato	9		<i>Amaranthus retroflexus</i> <i>Chenopodium album</i>	Lebanon	440
rice, paddy	6 after transplanting		<i>Echinochloa crus-galli</i>	Philippines	319

Crop	Weed-free period required after		Competing weeds	Location	Source
	Seeding	Emergence			
	— (weeks) —				
rice, upland		3	mixed annuals and sedges	India	460
sorghum	3		mixed annuals	Nebraska, USA	113
sorghum	4		mixed annuals	Nebraska, USA	115
soybean	4		<i>Ipomoea purpurea</i> <i>Digitaria sanguinalis</i>	Delaware, USA	557
soybean	2		<i>Amaranthus retroflexus</i>	Delaware, USA	557
soybean	3		<i>Setaria faberii</i>	Illinois, USA	298
soybean		4	<i>Xanthium pennsylvanicum</i>	Mississippi, USA	42
soybean		6	<i>Ipomoea purpurea</i>	Arkansas, USA	318
soybean	3 to 6		<i>Hibiscus trionum</i> <i>Abutilon theophrasti</i> <i>Sida spinosa</i>	Kansas, USA	182
soybean		6	<i>Amaranthus hybridus</i> <i>Acnida altissima</i> <i>Setaria viridis</i>	Nebraska, USA	110
soybean	4		<i>Sorghum bicolor</i>	Kansas, USA	585
sugarbeet		6	<i>Kochia scoparia</i>	Colorado, USA	546
sugarbeet	10		<i>Echinochloa crus-galli</i> <i>Chenopodium album</i>	Washington, USA	152
sunflower	4 to 6		mixed annuals	Georgia, USA	280
wheat, winter	2		<i>Bromus tectorum</i>	Nebraska, USA	560

While specific comparisons are difficult for data covering beans to yams, and ranging from the West Indies to Argentina to England, some conclusions can be drawn concerning the effect of competition duration.

As stated, "critical period for weed control" generally defines the time span when weeds present from the beginning of the crop cycle must be removed, or the point after which weed growth no longer affects crop yield (371). The term also can describe the early weeks of crop growth when weeds need to be controlled to prevent yield reduction. Not all studies have been designed to define a critical period; hence, it is not possible to decide if such a period exists for every crop. If a difference between the length of weed-free period required (Table XV) and length of weed competition tolerated (Table XIV) can be assumed to indicate a critical period, then discussion can follow (Table XVI).

However, such data extrapolations are seriously challenged by several papers from England indicating the absence of any "critical period" for weed competition in red beets (245), summer lettuce (426), summer cabbage (425), and broad beans (247). Tables XIV and XV reveal differences in the periods for these crops, but a single weeding at an intermediate point in time sufficed. However, the circumstance varied for onions (246, 422), a crop manifesting slow germination, slow early growth, and susceptibility to weed competition effects for a major portion of the growing season. The Table XVI extrapolations also can be questioned on the basis of differences in competition from specific weeds as illustrated by the data on soybean competition with *Setaria faberii* (299, 300), and *Ipomoea purpurea* (380). The *S. faberii* data support the critical period hypothesis, but those on *I. purpurea* do not. This instance

TABLE XVI

Crops with an apparent critical period for weed competition.

Crop	Weed-free period required (weeks)	Length of competition tolerated (weeks)	Source
bean	5	8	150
corn	3	6	299, 300
cotton	6	8	85
peanuts	4	8	235
	3	6	250
potato	6	9	440
rice, paddy	3	6	319
soybean	3	8 to 9	299, 300

emphasizes a need to consider specific weed-crop competition rather than general cases.

Additional complications arise from inclusion of fertility or plant spacing as variables. Li (316) proposed that the first 2 to 3 weeks after crop emergence comprised the most important period of weed competition in corn. During this time weeds completed 15 to 18% of their total growth, but corn grew only 2 to 3%. Weedy corn yield decreased—as competition period lengthened—at high fertility, but not at low fertility (Table XVII). These data were confirmed by Bowden and Friesen's study of *A. fatua* in wheat and flax (74) and Bell and Nalewaja's (49) work with the same weed in barley and wheat.

TABLE XVII

The influence of soil fertility on weed competition in corn (316).

Duration of weed competition (weeks)	Yield of weedy plots	
	Low fertility (bu/A)	High fertility (bu/A)
2	111	130
3	114	110
5	114	101

Oliver et al. (379) illustrated the predictable relationship between competition duration and weed spacing. *Ipomoea purpurea* spaced 15, 30, or 61 cm in the soybean row needed 6, 8, and 10 weeks of competition before yield was negatively affected. In fact, numerous studies supported this finding (17, 33, 52, 86, 87, 157, 271, 296, 352, 353, 468, 471, 524, 532, 548, only a few cited).

Relatively few data address the influence of weed planting date on competition. Vengris (526) checked growth and development of *Amaranthus retroflexus* and *Setaria lutescens* as affected by time of seeding. The earliest seedings produced the tallest plants and highest weed yields. The interval between emergence and maturity decreased progressively as seeding date was delayed. Dawson (157) showed that annual weeds emerging in sugarbeets after July 1 (the last cultivation) were suppressed by the crop and did not affect yield. Late emerging weeds were competitive in a one-third or one-half stand. Planting *Sida spinosa* or *Hibiscus trionum* with soybeans reduced yield 33%. When weeds were planted 10 days after soybeans, yield fell 20%; weeds planted 20 days after the crop did not affect yield (182). *Setaria faberii* seeded in a band over crop rows, 3 (or more) weeks after corn or soybeans, did not reduce yield of either crop (298).

Another consideration emerges from the data of Welbank and Witts (555) who showed that earlier planting and consequent early

weed emergence may not favor crops because cultivations prior to later planting could destroy many seedlings as they emerge.

Kasasian and Seeyave (285) proposed the working hypothesis that crops require a weed-free respite for one-fourth to one-third of the crop's growing period. Their data confirmed this for beans, tomatoes, sweet potatoes, pigeon peas [*Cajanus cajan* (indicus)], sugarcane, and yams. The study was based on an earlier paper by Nieto et al. (371) reporting that beans and corn were most susceptible to weed competition during the first 30 days of a 130 to 135 day growth period. The data reviewed generally support Kasasian and Seeyave's hypothesis, but with the caveat that while it is a useful generalization, specific weed-crop interactions must be considered.

These concepts and data provide a basis for specifying required periods of weed control, regardless of methodology, and for comparing the value of methods with varying persistence (423). Importance attaches to the specific crop(s) and weed(s) competing and to what resource they are contesting under the prevailing environmental conditions. All of the crops surveyed (Table XIV) can withstand weed competition for some duration after planting. Yield-reducing competition is likely to occur much earlier in the season, if moisture, rather than light, is the primary limiting parameter (154). □

VII.

Competition for Nutrients

Axiomatically competition for nutrients constitutes an important aspect of weed-crop competition. One view (318) suggested that weeds provide keener competition for nutrients than for water. However, weed competition experiments are often difficult to interpret accurately because weed density and crop yield may be subtly affected by fertility differences (554).

Vengris et al. (528), supporting clean cultivation of corn, contended that weeds compete for essential nutrients and decrease crop yield even at high rates of fertilization. Other work on the relationship between weed infestation, fertility, and yield produced similar data. Increases in wheat yields resulting from fertilizer treatments were approximately equal to increases resulting from weed removal (360). Another experiment reported an average air-dry yield of weeds four times as great on fallow plots as on plots cropped with spring cereals; fertilizer applications increased weed yields on both (499).

In reviewing sixty papers in 1976, Alkamper (16) provided an excellent analysis of weed-fertility interactions. The study emphasized that weeds usually absorb fertilizer faster and in relatively larger amounts than crops and therefore derive greater benefit. The observation receives support from other studies. For example, Vengris et al. (528) compared the relative nutrient uptake of weed free corn, corn infested with *Amaranthus retroflexus*, and *A. retroflexus* alone (Table XVIII).

TABLE XVIII

Comparison of nutrient content of weed-free corn, corn and *Amaranthus retroflexus*, and *A. retroflexus* alone (528).

Species	Relative nutrient content				
	N	P ₂ O ₅	K ₂ O	Ca	Mg
weed-free corn	100				
corn infested with <i>A. retroflexus</i>	58	63	47	67	77
<i>A. retroflexus</i>	102	80	124	275	234

In fact, fertilizer may stimulate weed growth to the extent that crop loss actually increases. An obvious conclusion is that weed control cannot be achieved with fertilizer. Additionally, maximum benefits from fertilizer accrue only to crops with relatively few weeds.

Several studies confirm that fertility control falls short of being an effective weed control technique. However, the proposition that yield reductions increase under high fertility stands as a point of disagreement. DeDatta et al. (159) found yields of IR-8 rice dropped more under high, compared to ordinary, fertility, but that the opposite held true for the cultivar H-4. Noda et al. (347) discerned no effect of fertility on the rice cultivar Shiranuki. Competition of several annual weeds with two varieties of upland rice primarily centered on nitrogen (129).

In competition with *Polygonum convolvulus*, wheat and flax incurred more yield reduction when fertilized. Flax, in competition with 5 *P. convolvulus*/ft², experienced a 9.5% yield drop with fertilization, versus zero reduction in the absence of fertilization. Sixteen weeds/ft² reduced yield 20% with fertilization, but only 4.5% without (361). Fertilizer increased flax seed yield losses at high seeding rates and generally doubled *P. convolvulus* dry matter production (213). Yield reductions in unfertilized and fertilized flax seeded at 14 lb/A were greater than 6 bu/A one year. In plots seeded at 70 lb/A, yield losses tended to be about 2 bu/A higher when flax was fertilized. Fertilizer stimulated growth of both species, but the weed benefitted more because of more efficient nutrient and water usage (213).

Forty *Avena fatua*/yd² reduced flax yield up to 74% on stubble land, but only 44% for a crop planted on fallow land (46). As few as 10 *A. fatua*/yd² reduced yield 57% on stubble land and 20% on summer fallowed land. In the same experiment (46), 10 *A. fatua*/yd² also depressed wheat yield, but to a lesser extent than flax. However, yields consistently were weakened approximately 50% more when wheat was not fertilized. Pande (389) reported wheat responded more to weeding at low fertility levels. Thurston (513) showed that nitrogen fertilization equally increased yields of cereals and *A. fatua*, but did not alter the proportion of each in the stand (512). Nitrogen increased barley culm number and yield as well as barban did (331), but did not affect the basic weed-crop relationship in cotton (95).

In their pioneering studies of competition between cereal crops and annual weeds, Blackman and Templeman (63) revealed that, in a normal rainfall year, low-growing weed species competed for nitrogen while emergent species competed for light as well. High rates of nitrogen fertilization were recommended as an economical

means of suppressing moderate weed populations. When graded rates of nitrogen were added to weed-infested crops, weeds reduced crop growth less at higher nitrogen levels. In some studies, added nitrogen increased weedy crop yields to, or above, the level of clean crops. Myers and Lipssett (359) found early competition for nitrogen depressed wheat yield and that spraying *Chondrilla juncea* 2 months before wheat planting improved crop yields.

Modifying nitrogen supply affected interference between either kale or wheat and *C. album*. The ability to compete for nutrients accounted for an important part of *C. album*'s success (553).

Hawkins and Black (238) demonstrated the interaction of competition for nitrogen and other factors. Adding nitrogen and removing *Emex australis* bolstered wheat yield. The nitrogen effect was attributed to an increase in the number of grain-bearing tillers per plant. However, raising the nitrogen level to 400 lb/A apparently removed the limit. Yield was substantially greater for a weed-free crop than a weed-infested crop, whereas at lower nitrogen levels, weed-infested plots had given a greater response to nitrogen.

The interaction with temperature and growth is also important. Witts (581) obtained a lower response from wheat in England when topdressed with nitrogen in May as opposed to March, an effect that was accentuated by weeds.

Friesen et al. (201) obtained significant increases in protein content following weed removal in 22 of 60 Manitoba, Canada grain fields. The researchers suggested that weeds competed with grain crops for available nitrogen and that yield reductions, resulting from weed competition, generally were accompanied by reductions in grain protein content.

Lang et al. (308) theorized that maximum corn yields would occur at different plant populations under varying nitrogen levels. Their tests indicated that highest corn yields (75 bu/A) occurred at 12,000 plants/A with low nitrogen, 16,000 plants under medium nitrogen (92 bu/A), and at 20,000 plants under conditions of high nitrogen (118 bu/A). Other forms of competition—particularly for light—were also operative in intensifying nitrogen competition. They firmly established the general principle that as fertility level improves, the density required for maximum yield increases.

Staniforth studied the effect of *Setaria* spp. on corn yield (479, 481). Yield reductions averaged 10 and 5%, respectively, with applications of 70, and 140 pounds of elemental nitrogen/A. The greatest effects of *Setaria* spp. on corn yields occurred under low soil nitrogen conditions. Other work re-emphasized nitrogen's ability to minimize the effects of *Setaria* spp. competition. The experi-

ment illustrated the relation of nitrogen competition and corn variety. During two years corn/hundredweight of *Setaria* spp. for late-maturing hybrids was reduced approximately twice as much as early-maturing hybrids. Differences were accentuated by a 140 lb/A nitrogen fertilization rate. Results indicated the presence of a critical period in late-maturing hybrid growth corresponding to maturation of *Setaria* spp. The early hybrids would have already passed through such a period. Low level nitrogen plots manifested the greatest yield reductions (478); nitrogen competition abated as nitrogen fertilizer levels rose (372). Nieto and Staniforth found that *Setaria* spp. infested corn responded more than weed-free corn. However, *Setaria* spp. effect on sorghum was greatest in years with above average rainfall and supplemental nitrogen fertilization (191).

Sorption of nutrient ions indicates that corn and weeds primarily compete for nitrogen and water, but a sufficiency of either does not eliminate competition entirely (304). Kurtz et al. (303) intercropped corn and sod crops and produced 80% of normal yield when nitrogen was added to field corn infested with *Setaria* spp.

Staniforth's work (482, 487) with nodulating and non-nodulating isogenic lines of soybeans produced similar yield losses due to competition from three annual weeds. Not unexpectedly, he concluded that the competitive ability of this leguminous species was not limited by nitrogen supply.

Dotzenko et al. (175) showed that rate and time of nitrogen fertilization affected weed populations and, thus, number of weed seeds produced. Nitrogen applied to a crop grown immediately before sugarbeets produced greater weed problems in sugarbeets than when applied earlier in the rotation. Higher nitrogen rates had a similar effect. Extra nitrogen stimulated growth of *C. album* more than sugarbeets. Weed-free sugarbeet yield was unaffected by supplemental nitrogen whereas weedy crop yield was depressed by supplemental nitrogen (453).

The common phenomenon of border effect provides a simple and clear illustration of nitrogen competition (177). Border rows on unfertilized plots had higher yields than internal plot rows, while border rows on plots receiving 100 lb nitrogen/A had lower yields than internal rows.

Competition for nitrogen was reported in a greenhouse experiment by Donald (167) who emphasized the importance of keeping other nutrients, water, and light non-limiting. *Bromus catharticus* was grown at densities of 1, 3, 6, 12, and 50 plants/pot at 0, 150, or 700 mg nitrogen/pot. Only at the highest nitrogen level was a single plant unable to fully exploit the nitrogen supply; three plants were needed in that case. At 0 and 150 mg levels, yield was

not affected by number of plants; the lowest density of one plant/pot succeeded in using all the nitrogen while at the highest densities the supply was equally shared, thereby illustrating competition in its simplest dimension. All other factors were constant and in excess permitting only competition for nitrogen.

Thrasher et al. (510) studied competition of forage species with *Cirsium arvense* and found weed numbers increased with frequency of irrigation in plots fertilized with 100 lb of nitrogen or less. If added nitrogen was increased to 400 lb/A, thistle numbers decreased with the same frequency of irrigation.

Two experiments illustrate the importance of species interaction in nitrogen competition. Walker et al. (536) used labeled nitrogen sources to demonstrate differential use of nitrogen in monoculture as opposed to association. When growing alone, grass took up more soil nitrogen than clover. With an increasing level of added nitrogen, clover took up more and fixed less. When grass and clover were grown together, almost all added nitrogen was absorbed by grass while clover obtained its supply from symbiotic fixation. Willoughby (578), studying the same association, found that temperature exerted an important influence. If nitrogen was applied during higher temperatures, when more rapid seedling growth occurred, clover gained dominance. However, if the nitrogen was applied late in the season when temperatures were low, grass grew more vigorously than clover for the same reason.

The three most commonly limiting nutrients are nitrogen, phosphorus, and potassium. While nitrogen has been investigated extensively and may be the most important element in plant competition, competition may occur for any element required for plant growth. Science, however, lacks definitive explanations for the "what and why" of nutrient competition. Donald (171), in his introduction to nutrient competition, mentioned that a secondary effect must be considered. Success in gaining a larger share of available nutrients may stimulate growth increases resulting in dominance as much from competition for light as for nutrients.

Relatively little investigation has been aimed at nutrients other than nitrogen, leading to insufficient knowledge of plant competition for them. Willoughby (578) noted that a decrease in grass production evolved almost wholly due to imperfect nutrition involving nitrogen and phosphorus. Mouat and Walker (355) decided that the basis of competition for phosphorus between species could be a function of root cation exchange capacity.

A study by Blaser and Brady (67) documents competition for potassium in a mixed culture. The work was designed to ascertain the effects of nitrogen and potassium fertilization on productivity and the botanical and chemical composition of a ladino clover-

grass mixture. Potassium alone generated an increase in total yield due almost entirely to increased yield of clover. When nitrogen and potassium were supplied, clover yield ebbed with little increase in grass yield. Nitrogen application probably intensified competition for potassium between grass and clover. As explained, grasses grew at lower spring temperatures and therefore obtained an earlier start on the potassium reserve; competition increased as temperatures rose and the legume began to grow. Application of nitrogen aggravated this situation because grass used it preferentially. Species tending to dominate in a given plant mixture are those affected most favorably by imposed and natural factors which influence growth rate (a point to be considered in preparing seeding mixtures).

Gray et al. (210) proposed a direct relation between root cation exchange capacity of grasses and clovers and competition for potassium. Potassium uptake demonstrated an inverse relationship to root cation exchange capacity of three grasses. Because of strong attraction and high potassium uptake by *Agrostis* spp. roots, practical rates of fertilization could not maintain an adequate potassium supply for associated ladino clover. Though inconclusive, the evidence does coincide with Mouat and Walker's observations (355) concerning a possible mechanism of competition for potassium and phosphorus.

Potassium deficiency primarily results in severe stunting. While weeds seem to be insensitive to low soil potassium, they do respond to added potassium (93, 264). Several weeds compete most aggressively in heavily fertilized crops. Hoveland et al. have categorized responses of several weeds to soil phosphorus and potassium (264). Phosphorus uptake is specific for different combinations of species as well as their stage of growth. Beans absorbed phosphorus from a smaller soil volume than roots of *A. retroflexus*, which had great lateral spread, or *Setaria viridis*, which had the deepest soil penetration (130, 131). The authors could not explain variable phosphorus content on the basis of competition. They found increasing weed or bean density decreased phosphorus uptake by beans. Weed plants actually had less effect on phosphorus uptake than other bean plants. Interrelationships of roots at soil microsites, where nutrient absorption takes place, were postulated to be important (131).

Both dry matter production and percent phosphorus or potassium in plant tissues held more constant for alfalfa than for *Digitaria sanguinalis*. In association, *D. sanguinalis* dry matter increased independently of alfalfa when both nutrients were plentiful, or when potassium was in low supply (290).

Walker and Adams (535) studied competition for sulfur in a grass-clover association. Under minimal sulfur conditions, grass

took up most of the compound and clover was depressed. When nitrogen was added, competition increased. Heavy applications of sulfur relieved clover suppression.

As mentioned, many weeds possess a higher mineral nutrient content and may be able to utilize nutrients at the expense of crop plants. *C. album* accumulated nitrogen and potassium at the expense of crop plants; *A. retroflexus* accumulated seven times as much phosphorus as associated bean plants (529). Corn grown on phosphorus deficient soil out-performed corn grown with weeds in plots treated with phosphorus (528).

Again, the feasibility of overcoming weed competition by fertilization can be questioned. An experiment by Edwards and Allard (183) illustrates the difficulty competition studies pose. Two barley cultivars were studied to assess light's influence on competitive ability; the scientists found no competition for light. One cultivar, while displaying a definite competitive advantage, did not possess any morphological or physical characteristic (such as height) assumed to be advantageous. However, the dominant cultivar began to develop a dense mass of crown roots at the jointing stage and may have become more efficient at gathering nutrients.

A study not to be overlooked by the student of weed-crop fertility interactions is the Park-Grass study at Rothamsted, England. One report, among many, is that of Williams (576). The numerous aspects of the Park-Grass study include the observations that phosphorus and potassium without nitrogen will stimulate legume growth at the expense of grasses, whereas nitrogen will stimulate grasses. Ammonium sulphate acidified soil and discouraged legumes. Varying combinations of the three major nutrients altered plant species dominance.

A later complementary study evaluated the influence of continuous fertility treatments on weed species in winter wheat over 47 years (38). Plots without any added fertility (or lime) produced fewest species. Populations diversity increased as nutrients were added. The highest number of species occurred on plots receiving complete fertilizer plus lime.

Other research has revealed nitrogen's ability to increase growth of grasses and depress growth of associated leguminous plants (67, 165, 354, 510) through an as yet unknown mechanism. Nitrogen placement did not affect broadleaf weed populations in rainfed wheat, but soil compaction reduced weed numbers (465). In another study, high nitrogen levels reduced effects of *Agropyron repens* on relative root growth rate and net assimilation rate of *Impatiens parviflora*, but had no effect on relative leaf growth rate (552). Water proved a more important competitive factor than nitrogen. □

VIII.

Competition for Water

The importance of water to all forms of life precipitates major national and international concern. As an essential factor in the growth and functions of plants, water is not an inert component. Its deficiency restricts many crops' growth and its presence or absence commonly determines geographic limits of crop production.

Despite water's great importance to all life, too little is known of its complex relationships in plant competition. Milthorpe (345) provided the general principle that the greater a plant's leaf growth before it comes into contact with another plant, the more extensive will be its root system and the less it is likely to suffer from drought. He said, "The higher the density, the smaller the plant at any time during ontogeny, and the higher the water content at which shortage of water is experienced." Over a wide range of densities with complete cover, total dry matter yield per unit area does not vary as long as the root zone is supplied with adequate water and nutrients.

Slyter (466) studied the water relations of cotton, peanuts, and grain sorghum under naturally low rainfall conditions in the non-agricultural region of Australia. He disclosed that these crops differed in their ability to exploit available water supplies primarily due to variation in root system extent. Cotton suffered the greatest water stress and sorghum the least. Sorghum generated the most developed and extensive root system plus the most effective control of transpiration. By contrast, cotton manifested inefficient internal water regulation and a poorly developed root system 2 feet (or more) below ground surface.

Any plant's capability to successfully compete for water, according to Donald (171), depends on the rate and completeness with which it utilizes the soil water supply, a characteristic that relates to attributes of the genotype within the particular environment. These attributes are relative growth rate, corresponding earliness of water demand, and rate of root extension.

Crop growers may be assumed to have known from the advent of farming that crops will yield more under favorable moisture

conditions. Knowingly or unknowingly, farmers have adapted seeding rates to moisture conditions. In other words, annual crop planting and optimum density will be less in a dry environment than in a wet one (171).

Creating a field or laboratory situation wherein a single factor determined the level of crop competition would be difficult if not impossible. The three primary factors (water, light, and nutrients) interact extensively and a change in any one affects the plant's ability to respond to the others. Because it is not feasible to deal with all factors and their interactions, researchers must select among them (317). A definite interaction exists between nitrogen and water. A nitrogen shortage affects transpiration; possibly a lower water use level may occur compared to ample nitrogen supply conditions. If interest focuses on yield (dry matter production), consideration of just water and light is insufficient, because of the impact of nutrients on photosynthesis (317). Lof (317) examined water use efficiency and competition between two arid zone annual grasses. *Hordeum murinum* is economical in its use of water and *Phalaris minor* is profligate. He proposed that the saver—*Hordeum*—is suppressed by the spender—*Phalaris*—which consumed most available water and nitrogen. Lof continued:

"Still, *Hordeum* has two advantages over *Phalaris* which make it stand the competition quite well; first, it exhibits a rapid early growth, when conditions are favourable, investing little in the production of roots, and covering the soil with many nearly horizontal tillers. This gives it a lead over *Phalaris* in claiming the available geometrical space. Secondly, *Hordeum* completes its phenological cycle much faster than *Phalaris*: its seeds are ripe when *Phalaris* is only starting to flower. When flowering, most of *Hordeum*'s photosynthetic activity takes place in its awns.

Phalaris reaches much higher productions but its relatively 'solid' behaviour renders it unable to eliminate a rapid and efficient opportunist, like *Hordeum*" (317).

The work of Kurtz et al. (303, 304, 305) emphasizes the interrelationships of competition for water and nitrogen. The studies disclosed that when water and nitrogen were applied to corn grown in narrow tilled bands interplanted with competing pasture crops of red or sweet clover (*Melilotus* spp.), yields could be altered drastically. Denying water and nitrogen resulted in roughly a 75% drop from conventional yield. Adding nitrogen and water restored yield to 85 to 90% of conventional production. All variations of nitrogen and water were tried in this analysis of the components of competition.

Hackbarth (217), in a study of competition between corn and weeds, neither ascertained whether water or fertility became limiting first nor established a precise relationship. Addition of water alone increased dry matter, but increasing fertility alone often did not.

Stahler (477) compared competition for light with soil moisture as a factor in the success of *Convolvulus arvensis*. He concluded that, where competition for water develops, *C. arvensis* competes well with all crops. However, if this is not the case and nutrients are adequate, light becomes the prime focus of competitive forces.

Wiese (564) and Wiese and Vandiver (567) demonstrated soil moisture's great influence on weed and crop competitive ability. Their results offer at least one reason for the domination of certain weed species in particular regions. Corn, sorghum, *Echinochloa crus-galli*, *Xanthium pensylvanicum*, and *Digitaria sanguinalis* achieved maximal growth in wet soil. Dry soil stifled growth of these species; *X. pensylvanicum* died in the driest soil. *Kochia scoparia*, *Salsola kali*, *Schedonnardus paniculatus*, and *Solanum rostratum*, compared to the aforementioned species, produced less growth under wet conditions, but were unhampered in dry soil. In fact, *S. kali* doubled its dry matter production in dry soil. Species that achieved greatest growth in wet soil were most adversely affected by competition and water stress. Plants that produced little growth in wet soil actively competed in dry soil (567).

Water seemed to be the primary factor in below-ground competition between *A. retroflexus* and tomato (348). *A. retroflexus* dry matter production decreased as moisture stress increased. The same weed, according to studies by Keeley and Peters (289), suffered more than birdsfoot trefoil at low moisture levels.

Research has established that competition for moisture usually occurs with other forms of competition (168, 171, 303, 304, 317, 367, 486, 490). Nelson and Nylund (367) found competition between weeds and peas primarily centered on light and water depending on weed height. In other research, Bauer et al. (43) observed that, as precipitation or stored soil water increased, response of barley or spring wheat to nitrogen fertilizer increased.

A study of the effects of three *Setaria* species on soybeans (486) attributed yield depressions to competition for available soil water and light because of shading effects of *Setaria*. *S. faberii* proved the most effective competitor by dint of its more vigorous growth and height. *Setaria* competition caused soybean yield reductions to be minimal when one of three conditions prevailed:

1. soil water adequate for the entire season;
2. soil water limiting for the entire season;

3. soil water limiting to the end of July and adequate to plant maturity (yield reductions in this situation averaged 14%).

Staniforth (480) concluded that water played a very important role and rainfall at a propitious time could reduce *Setaria* competition.

Moolani et al. (352) showed the importance of May to July rainfall in determining the extent of early weed competition in corn and soybean.

The interaction between rainfall and optimum density was well illustrated in an early experiment conducted by Karper (283) in Texas (US). Results help clarify variation between genotypes and their rainfall-density relationship. Crops were spaced at 3 to 36 inches in the row, with 36 inches between rows. Milo generated greatest yield at wide spacings in either a wet or a dry season, but Kafir had an optimum density in a wet season ten times that in a dry season. The difference was attributed to the fact that milo tillers to a great extent and the number of tillers increased with row spacing. Supporting data, from Kansas (211), revealed that the optimum density for sorghum production rose as the number of irrigations increased. However, weed competition did not affect sorghum water use efficiency, a finding that agrees with those of Russell and Danielson (434) in corn.

Wiese et al. (565) reported that sorghum grain yield losses caused by uncontrolled weed growth varied from 8 to 41%. Sorghum, under high moisture conditions, competed most effectively when planted thickly in narrow rows; with less moisture, more effective competitiveness occurred with wide row seeding. Yields in another sorghum study (192), based on competition with *Acnida altissima*, evidenced the most severe reduction during a year of high rainfall when supplemental nitrogen was applied.

Growing alone, wheat increased both its dry matter and nitrogen content more than *Polygonum convolvulus* as soil moisture content rose. Competition between the two altered the situation (190). The weed used less water to produce a gram of dry matter than wheat when each was grown alone. In competition, they were intermediate in water use. Another *P. convolvulus* competition study, with flax, revealed that the weed competed more effectively because it more efficiently used water for nutrient uptake and growth (213).

Alfalfa and *Chondrilla juncea* mainly competed for water, but when *C. juncea* competed with annual medic, emphasis shifted to light. Alfalfa, because of its perennial character, consistently suppressed the weed more effectively than annual medic (556). □

IX.

Competition for Light

Carbon assimilation, or photosynthesis, by green cells produces carbon compounds from carbon dioxide and water with oxygen formed as a by-product. In this process, cells absorb and transform light energy into chemical energy bound into products and intermediates that become available for the plant's functional needs or, for man. Photosynthesis primarily occurs in plant leaves, thereby reinforcing the importance of the leaf in competition. Clements (139) realized, in 1907, that the amount and disposition of leaf surface defined a decisive plant competition factor.

Light constitutes a key external variable of the photosynthetic process. It is difficult to imagine that plants, growing in isolation at most latitudes, could suffer a deficiency of light. Growers usually do not regard light as limiting. Because light does not exist as a pool or a readily available supply, it cannot be controlled by a grower as the nutrient or water supply can. Competition for light, one of the most common forms of competition in the plant community, may occur whenever one leaf blocks off light from another leaf, either on the same, or a different, plant. In fact, competition for light in field crops may operate throughout the crop cycle, except when plants are young.

Petrus de Crescentiis (cited in 140), who advocated cutting trees first where the stand was thickest, may have been thinking primarily of light competition in his very early work with forest communities. The dramatic difference in light penetration can be experienced readily in a forest, but the true role of light competition in common crops and forest remains enigmatic.

Several investigators have stressed the importance of light competition. Donald (169) found competition for light was an important component of total competition when two grasses grew in association at a nitrogen supply level that restricted yields. Stahler (477) determined that, under ample soil water and plentiful nutrient supply conditions, light became the prime factor around which competitive forces developed. The same observation has been recorded by others (62, 241, 492).

Some of the most impressive research concerning light competition has been conducted on small grain crops and pastures. Jarvis

et al. (276) concluded there was no effect from a companion seeding of grasses or legumes on yield of grain, straw, grain weight, or nitrogen content of barley grain. Therefore, competition could only have occurred for light. Oats seeded at 0.5 to 3 bu/A produced a constant yield of dry matter in work by Bula et al. (99). Competition for light caused yields of associated legume species to fall from nearly 50% of the total to less than 10%, though the number of legume plants remained constant.

Maximum pasture production requires that all available light be utilized by photosynthetic tissue. A continually changing relationship exists between growth and light interception by pasture foliage. Several factors—stage of growth, species, and season of the year—affect the relationship (81). In grass-clover pastures, adding nitrogen stimulated grass growth, created a larger leaf canopy over clover, reduced light intensity, and thus depressed clover growth (492). Evidence of a similar light-nutrient interaction was observed between grass and white clover (354).

Wilkinson and Gross (569) found light and water were critical factors in establishment of ladino clover in well-fertilized orchard-grass sod. Root competition dominated and reduced clover dry matter through competition for water. The authors suggested that their results contradicted Donald's proposition (171) that light is primary in such situations because it is instantaneously available and cannot be accumulated or stored.

The intensity of root competition was found to be intimately related to light intensity in studies conducted by Witts and Welbank (582). They explained that, "Low light intensities so diminished the requirement of sugarbeet plants for nitrogen that their growth was unaffected when part of the nitrogen supply was removed." Alternatively, low light intensity so restricted the growth of sugarbeet tops and roots as well as competing *Agropyron repens* that the roots intermingled less. Hodgson and Blackman (255) concluded that, "When the light gradient is such as to restrict the internal supply of substrates, the growth of those organs with the least competitive ability is arrested first." In the case cited, roots may be such organs.

Most physiological studies of photosynthetic efficiency, or the efficiency of the leaf, have been performed with isolated leaves or, perhaps, even *in vitro*. Results of these studies cannot be extrapolated to explain the effects of competition or competitive stresses. Plants in agriculture grow not in isolation, but in communities with a wide range of microenvironments for light competition. However, basic studies can provide important clues as to the direction of productive field research.

"Competition for light is not immediately competition between species, nor even between plants. It is competition between leaves," Donald observed (171). If one leaf lies above another, then the depression of the photosynthetic rate of the lower leaf will be the same, whether the superior leaf is of the same plant or another. Thus, the vital relationship is one of physical position. A plant with less total foliage may be the strongest competitor because it displays its limited foliage to greater advantage (170); cereal grains rising above weeds provide an example, so too the arrangement of leaves in the wild and cultivated sugarbeet studied by Watson and Witts (541). Therefore, immediate competition for light occurs between leaves, not between plants (492).

Measurements of light intensity's effect on isolated leaves was found, by Black (59), to be an unreliable guide to the effect light intensity exerted on stands of self-shading plants. As plants develop, leaf area index increases due to changes in leaf morphology. At low radiation levels, growth rate can fall to zero at high leaf area indices (61). Both maximum growth rate and optimum leaf area index increase with radiation. The index is dependent on incident radiation and independent of temperature (61).

A solitary plant, free from competition of any kind with neighboring plants, may have its lower leaves so shaded that they die. While competition for water or nutrients may occur within a plant, rarely is it of this intensity. The basic reason: light is not re-distributed (170). Plants growing with a localized concentration of fertilizer available to a few roots will fare better than plants with a lesser concentration available to their entire root system, a redistributional affect not applicable to light. A shaded leaf may be unable to rise above its compensation point leading to death regardless of light relationships of other leaves on the same plant. A corollary to this reasoning suggests that competition for light does not vary with light intensity (170). Although a leaf canopy may manifest greater development under high light intensity, internal competition remains severe.

Experiments comparing whole plant photosynthetic rates with those of leaves, at varying light intensities, further emphasize the relation of plant parts in light competition. Heincke and Childers (240) noted that individual apple tree leaves became light-saturated at one-quarter to one-third full sunlight, whereas the tree evidenced almost linear dependence on light intensity up to 8000 foot-candles. Similarly, Kramer and Clarke (302) found individual pine needles light-saturated at 3500 foot candles (one-third full sunlight), a point of only 60% light-saturation for pine trees; young pine trees increased their photosynthetic rates up to 10,000 foot-candles. Hesketh and Musgrave (242) recorded a progressive

photosynthetic rate increase for individual corn leaves up to 10,000 foot-candles.

Watson's (538) introduction of the leaf area ratio, or index, led to clarification of some light relationships. Watson introduced, "the measure of leaf area which is relevant to agricultural yields, that is, the weights of different crops produced per unit area of land is the leaf area per unit of land" (538). Thus, the concept has evolved that the area of leaves per unit area of ground and the light-receiving ability of those leaves have the greatest influence on photosynthesis and crop growth, rather than any differences in the efficiency of the process between leaves or plants.

In later work, Watson (539) said that little opportunity existed to increase yields by changing net assimilation rate (NAR). A crop such as sugarbeets may show a high NAR with low leaf area. The yield can be improved by encouraging development of greater leaf area. Early planting, one obvious means to this end, aids sugarbeets by creating a longer season and a more extensive photosynthetic surface earlier in the season.

Stern and Donald (491) presented results indicating that, for any level of radiation, an optimal leaf area index occurred corresponding to maximum growth rate. Value of the optimum index increased directly with radiation intensity.

Other studies (62, 148, 540) also demonstrated the existence of an optimum leaf area index. Watson, working with sugarbeet and kale, demonstrated the variability in this optimum. With leaf area indices of 5.3, 4.2, 2.9, and 1.6, kale reflected an optimum range of 3.0 to 5.4. Sugarbeets showed no increase in growth rate up to a leaf area index of three. Thus, the optimum leaf area index is not static but will change as leaf competition changes with light intensity. As light intensity increases, optimum leaf area becomes greater (61, 171, 491); conversely, as leaf area increases, maximum crop growth rate demands more light.

The preceding does not imply a lessened importance of NAR in crop growth and competition. Moursi (356) has shown that NAR peaks with no weeds and that weeds reduced relative total growth rate and relative leaf growth rate. In a study of the net assimilation rates of wild and cultivated sugarbeets, Watson and Witts (541) found evidence for the influence of leaf angle on sugarbeet production. The early season NAR of wild and cultivated sugarbeets was the same indicating basic similarity in their leaf physiology. As the season progressed both varieties experienced decreased leaf efficiency though the wild beet decreased the most, a result attributed to greater intraplant leaf shading. Black (60) supports these observations and adds, in reference to subterranean clover, that in the absence of defoliation, the success of a given strain

under competition is associated with its potential petiole elongation, i.e., its height. Donald (171) has suggested, in regard to the study by Watson and Witts (541), that plant breeders may have unconsciously been selecting for such traits without really knowing why. The same comment could be made concerning Black's findings.

Plant height defines an obvious and very effective component of the competitive struggle for light. Clements et al. (140), referring to the definite influence of plant height, commented, "plants may be so nearly the same height that the difference is only a millimeter, yet this may be decisive since one leaf overlaps the other."

Moolani and Slife (353) and Moolani et al. (352) established that height constituted a most important factor in the competition of *Amaranthus hybridus* with corn and soybeans. Corn yield contracted nearly 40% when weeds were allowed to grow in a 6-inch band over the crop row during the entire season. The same weed and band width reduced soybean yield up to 65%. The researchers attributed the yield loss difference mainly to the shading effect of corn which was taller than the weed while soybeans were only half as tall as the weed.

Stahler (477), after studying crop plants vying with *Convolvulus arvensis*, theorized that competition primarily concerned water. Further experimentation revealed that, because of plant height differences, competition for light became most important if soil water was conserved (or ample) and nutrients were plentiful. Choice of crops and cultural practices used in their production, ran the conclusion, could be manipulated to make competition for light a limiting factor in *C. arvensis* development.

Work by Black (59) also focuses on the importance of plant height. At the first harvest of a meadow, the plants germinated from larger seed had larger cotyledons at emergence, were slightly taller, and possessed a greater leaf area index. Thus, the competitive relationship outcome was foretold. The initial advantage was compounded; small-seeded plants eventually received only 2% of the light and produced but 8% of the yield. Studying height influence in corn competition, Pendleton and Seif (401) used a tall and a short corn variety. The taller variety, because of its shading effect, gained an advantage.

Shadbolt and Holm (458) measured light penetration reductions extending to 85% at the highest levels of weed infestation in vegetable crops, as well as 20 to 75% leaf area decreases. William (571) observed that *Cyperus rotundus* in several vegetable crops primarily competed for water and nutrients. Light was important only during establishment, particularly so in carrots and garlic.

Knake and Slife (296) reported a decrease in light intensity, at the soil surface, in direct proportion to weed density in corn and soybeans. Lang et al. (308) obtained the same result with corn, but also stated that competition for light intensified with each increment of growth and population. Work by Bush and Staniforth (123) showed that shading the sides of soybean rows inflicted greater yield reductions than top shading, which occurred later in the season when weeds grew taller than soybeans. They also proposed that competition for light affected yield less under moderately to severely limiting soil moisture during mid-growing season.

Competition for light between *Kochia scoparia* and sugarbeets, as observed by Weatherspoon and Schweizer (548), was confirmed by Dotzenko and Arp (174). Measurements indicated significant light intensity reduction beneath a weed-free sugarbeet leaf canopy compared to a *K. scoparia* infested one. The team also noted light competition commencing very early in the growing season.

Thirty percent shade during early growth stages reduced growth and yield of tomato and *Amaranthus retroflexus*, but had little effect at later growth stages (346). Because *A. retroflexus* exhibited greater sensitivity to shade than tomato, close plant spacing reduced weed growth more. Stilwell and Sweet (496) grew two sweet corn cultivars and *A. retroflexus* in full or 50% greenhouse light for 1, 2, or 3 weeks after emergence. Three weeks of low light depressed fresh weights of both species nearly 50%. Full light for 1 week followed by half light for 2 weeks decreased sweet corn fresh weight 35%, but reduced *A. retroflexus* only 17%. The competitive relationship is obviously very different in tomato and corn vis-a-vis *A. retroflexus* illustrating a difficulty of precisely defining weed-crop interactions.

Unquestionably species differ in their response to light, a response important to the proposed biochemical basis for plant competition (56). Hesketh and Moss (241) measured variation in response of photosynthesis to light in several species. Corn, sugarcane, and sunflower did not show evidence of light saturation; nine other species became light saturated at low levels. Corn's response to light became more linear as carbon dioxide concentration increased from 223 to 500 ppm. These data can be related to competitiveness of the species observed.

Another study (185) pursued the question of why photosynthetic rates differ. Tropical grasses were found to possess a high ratio of internal cell surface exposed to air compared to cell volume. Also, these plants exhibited a unique arrangement of cells around vascular bundles, a characteristic which may permit absorption of a greater percentage of necessary nutrition and carbon dioxide.

Amaranthus sp. display both a photosynthetic rate and leaf anatomy similar to tropical grasses.

Burt and Wedderspoon (121) demonstrated that *Sorghum halepense* plants from different latitudes and temperature regimes varied in response to dark periods. When grown at a common site, the selections varied in dry matter accumulation and flowering, manifestations related to length of the dark period.

Weed seed germination can be influenced by light and light can be affected by filtration through plant leaves. The red portion of the light spectrum promotes germination and is absorbed by leaves. However, the far-red, germination inhibiting portion is transmitted (505). Irradiation with light filtered through tobacco leaves decreased germination of six weed species seeds pre-irradiated with red light, but increased germination of previously unirradiated seeds.

Donald (171) discussed the influence of climatic environment relative to light. In terms of competition, a particular contrast exists between light on one hand and water or nutrients on the other. In a region of adequate rainfall, competition for water decreases or becomes totally absent. The same is generally true of mineral nutrients. The case with light, however, is markedly different. A plant's shaded lower leaves suffer decreased photosynthetic activity and approach, or fall below, the compensation point. The same condition can exist despite increasing light intensity. The difference between the two situations lies not in the intensity of competition for the light as it is received, but in the depth of leaf cover preventing uniform receipt. Therefore, competition for light can be as acute at noon on a bright summer day as on an overcast day.

When studying the interaction of competition for two or more factors, one factor must be light. Clements et al. (140) proposed that competition for two factors will involve interactions allowing aggressor species to gain competitive advantage beyond that gained in competition for either factor alone. Donald (171) expanded on this concept by showing that competition for light, or any other single factor, involves at least two components which interact. For example, a heavily shaded plant suffers reduced photosynthesis leading to poorer growth, and a smaller root system, and ultimately reduced capacity for water or nutrient uptake. Water and nutrient restriction exists totally independent of direct competition for the two factors. □

X.

Competition for Other Environmental Factors

Clements et al. (140) limited competition primarily to nutrients, water, light, and perhaps space. However, plants require other factors for growth, but competition for these has not received extensive study. Isolating specific affects is difficult, plus the primary factors are so dominant in the environment and relatively easy to isolate for study.

Evans and Young (188) showed that particular microsites maintained the proper temperature as well as gaseous and water environment for seed germination. Germination of three weedy range species was favored by burial, pitting of the soil surface, and soil movement. Each element contributes to establishment of necessary microsites conditions which lead to germination and perhaps a competitive advantage.

Soil atmosphere, modified by shallow tillage, can increase emergence of some grass seedlings. James and Staniforth (274) did not find a consistent correlation between weed seedling emergence and measured soil atmosphere conditions, temperature, or moisture. A compensatory effect of soil moisture and temperature on the availability of carbon dioxide was observed in the field. In another study (380, 381) *Amaranthus retroflexus* and *Setaria faberii* were found to remove greater quantities of carbon dioxide than birdsfoot trefoil. Regardless of light intensity, *A. retroflexus* had a higher net carbon exchange rate than trefoil. At high light and temperature levels, the total net carbon exchange was 10 to 12 times greater for *A. retroflexus* than for trefoil 7 to 15 days after emergence. These were laboratory studies in which carbon dioxide concentration was held 20 to 60 ppm lower than the normal 300 ppm. No direct competition for carbon dioxide was observed in the field because atmospheric levels failed to approach the photosynthetic compensation point. However, more efficient utilization of carbon dioxide by weeds with high photosynthetic capacity contributed to their rapid growth and development and provided them a competitive edge.

One study by Beasley and Lawrence (44) emphasized the role of aquatic weeds as successful competitors for dissolved oxygen. Dissolved oxygen levels can be reduced as much as five times, which may kill fish and affect other aquatic organisms.

Temperatures of 80° to 90°F were the most favorable for growth of *A. retroflexus* and three *Setaria* spp. whereas *Chenopodium album* grew best at 60° to 70°F. Diurnal temperature fluctuations of 10° to 20°F improved growth of each of the five species. *S. faberii* possessed greater vigor than *A. retroflexus* in competition studies conducted under higher temperatures; *C. album* was the best competitor at low temperatures (45).

When differences in time of emergence, height, and leaf number were measured until plants were 15 cm tall (or for 40 days) under several temperatures regimes, corn performed best at all temperatures. Soybeans grew faster initially, but weeds grew faster after plants reached 15 cm (197). The relative amount of timothy in a weedy pasture decreased as temperature increased in the range 12°C day and 7°C night to 24°C day and 19°C night (221). In the same study, *Tripleurospermum maritimum* produced a greater amount of dry matter under low temperature regimes. Barnes and Peters showed that *Allium vineale* had a photoperiod and vernalization requirement for scape development (40). Temperature during growth also determined dormancy traits of aerial bulbs.

Hoveland and Buchanan (263) found four weeds that were highly tolerant of a soil pH of 4.7. Corn, soybeans, and *Cassia obtusifolia* manifested medium to high tolerance of acidity. Cotton and three other weeds were medium to low in their tolerance of acidity, while sorghum and two additional weed species could not tolerate acidity and actually suffered manganese toxicity. The authors concluded that soil pH may be a determinant of the weed species observed and thus the competitive situation.

A unique study showed that yield of oats was depressed in competition with barley because of damage by cereal root eelworms (*Heterodera avenae* Woll.) (462). Experiments in monoculture did not show any effect on yield when nematodes were present. □

XI.

Specific Aspects of Weed Competition

Certain weed-crop competition elements, while not falling under the previous headings, interact with other factors to affect competitive relationships. These have not been investigated as frequently as density, duration, nutrients, water, or light. However, they need to be considered when interpreting or planning competition studies. These factors are:

- A. spatial arrangement of plants;
- B. seeding rate;
- C. tillage;
- D. crop sequence;
- E. genotype.

A. Plant Arrangement in the Community

In his 1762 publication, Jethro Tull (519) recommended up to 5 feet between corn rows to facilitate "horse hoeing," an early consideration of plant arrangement, and one of few. Current literature does not generally include data supporting the traditional 7-inch drill row for small grains, or the 30- to 36-inch corn row. Logically, these patterns can be questioned as being optimal or if departures from them would be profitable.

Kiesselbach (292) observed that yield of a given plant variety fluctuated within broad limits as a result of different spacing. Hodgson and Blackman (254) found that row spacing of 7, 14, and 21 inches had no detectable influence on *Vicia faba* total yield if the number of seeds/A remained constant. They also noted some evidence that, in stands of two or more species, the arrangement pattern may influence the balance between species.

Hallgren (220) studied row spacing affect on pasture species. Red clover strongly shaded competitors at 5 and 25 cm row spacings as did orchard grass, though the latter continued to do so in 40 cm rows. Yield in narrow rows peaked, but decreased with in-

creased spacing although the distinction became muted with time. Annual broadleaf weeds dominated the wide row culture while creeping perennials comprised the major share of narrow row flora.

One early study (568) contends that the nearer the arrangement of plants approaches a uniform distribution, the greater will be the yield. Other things being equal, the narrower the distance between rows—until it equals the space between plants—the greater the yield, a condition confirmed by Montgomery's (350) corn experiments early in the century. Additional evidence derives from Ulrich's greenhouse work (520) with sugarbeets. A constant beet root yield per unit area was obtained for areas fully occupied by leaves. This result implies that uniform spacing or seed rate in rows is unnecessary so long as spacing permits full leaf coverage.

In soybeans, Wiggans (568) found that the more uniform plant distribution on a given area the greater the yield. Any increase in inter-row distance (from 8 to 32 inches) decreased yield. Plants spaced from $\frac{1}{2}$ to 6 inches in the row did not affect yield. Hinson and Hanson (253) discovered that more open spacing of soybeans caused increased branching and that this characteristic varied directly with photoperiodic response.

Several workers have reported that narrow spacing between soybean rows increases yields. Lehman and Lambert (315) and Burnside and Juricek (110) found two varieties produced greater seed yield in 20-inch rows compared to 40. The latter team also obtained higher weed yields in wider rows. The highest seed yields occurred in 10-inch rows, but 5-inch drill rows produced the highest dry weight. Maximum leaf area index correlated with highest dry weight yield, but not highest seed yield (550). Staniforth and Lovely (489) achieved best yield (40 bu/A) from rows 12 inches apart. Four rows, or four pairs of rows, in 120 inches reduced yield about 5 bu/A. Wax and Pendleton (543) gained increases of 10, 18, and 20% for rows spaced 76, 51, and 25 cm apart compared to 102 cm.

Narrower soybean rows generate earlier shading of the area between rows with consequent suppression of weed growth (108, 110, 404). Soybeans grown in 20 or 24-inch spaced rows required no more than one cultivation (when a herbicide was used), while those in 32 and 40-inch rows always needed one and often two cultivations (404). Weeds emerged for the first 6 weeks after planting when soybeans were planted in 20-inch rows; emergence lasted an additional week when row spacing doubled (110). Soybean populations of 39,200, 78,400, and 156,200 plants/A allowed weed yields of 900, 570, and 470 lb/A, an affect attributed to earlier shading

and more vigorous competition in the more dense crop population (110).

For sorghum, higher plant populations and narrower rows reduce yield losses as weed competition increases (104, 117). Weed competition exerts greater influence on sorghum yields than row spacing or plant population. Burnside and Wicks (115) showed that yields in hand weeded plots held steady for sorghum populations of 69,000 to 104,000 plants/ha, or row spacings of 51 or 102 cm. Mann (326) produced equal yields of dryland sorghum from 21 and 42-inch rows when planting the same amount of seed per acre. He concluded that plant population had more effect on yield than row spacing.

Porter et al. (412), presumably because of more efficient resource use at narrower spacing, found irrigated grain sorghum grown in 12 or 20-inch rows produced higher total yields and more grain per inch of water used than sorghum in 30 or 40-inch rows. A similar increase materialized when 40 and 20-inch rows were compared by Stickler and Anderson (493); the narrower rows enjoyed 12.6% greater yield attributed to increased tillering and larger heads. A 6% advantage was obtained in an earlier study (494).

Row spacing affect on weed control in cotton was documented by Rogers et al. (431) (Table XIX). With *Amaranthus retroflexus* as the dominant weed, row spacing developed importance only when weeds became established after cotton. Cotton in narrow, weed-free rows did not out-yield standard 106-cm rows, but required less intensive weed control (431). Row spacing, as a factor in flax culture, became more important under weedy conditions. Yield from weed-free plots were increased by condensing row spacing from 30 to 7.5 cm (8). Flax in narrow rows better withstood competition from late emerging weeds by virtue of more extensive and earlier ground cover.

TABLE XIX

Influence of row width on weed control needs in cotton (431).

Row width (cm)	Period of weed control required of maximum yield (weeks)
53	6
79	10
106	14

Hoff and Mederski (256) worked with corn at densities ranging from 10,000 to 20,000 plants/A and gained 5 to 10 bu/A for

equidistant spacing over random spacing in rows 42 inches apart. Fine and Fletchall (193) said greater interspecific competition and less intraspecific competition occurred when corn was planted in 20-inch rows as opposed to 30 or 40.

Pendleton and Dungan (400) considered the effect of different oat spacings on the growth and yield of oats and red clover. They did not find any oat seeding arrangement wherein the clover population, early growth, or yield equalled that of clover grown alone.

In the absence of weeds, peanut yield increased as row width decreased from 80 to 40 to 20 cm (90). The dominant weeds (*Cassia obtusifolia* and *Desmodium tortuosum*) grew less vigorously among peanuts planted in narrow rows.

At wide row spacings, interspecific competition was more important in snap beans, sweet corn, and onions. However, as row width decreased, intraspecific competition became important (574). Pod weight and pod weight per bean plant were reduced more by weed competition in wide rows.

Very few experiments have considered the possible effect of row direction. The results of work with oats by Pendleton and Dungan (400) indicated that rows in a north-south direction invariably out-yielded those seeded east and west. Other experiments cited by Donald (171) are those of Dungan et al., 1946, and Santhirasegram, 1962, both conducted in India. The effect has been attributed to light, with greater shading on the lower leaves of plants in east-west rows.

Donald (171), in an examination of plant arrangement in the community, concluded that, "the positive correlation of yield and density in individual foot lengths in a wheat crop is the outcome of competitive relationships between rows and because of plant plasticity, uneven sowing will not affect wheat yield as long as the plants are within reach of distant soil and light. The degree of unevenness of sowing done by a wheat drill does not affect yield."

This conclusion, although based on wheat, provides an hypothesis on which to base further research; also, support for it stems from work by Kiesselbach and Weihing (293) who demonstrated how corn plant plasticity could eliminate most of the effects of uneven stands on yield.

B. The Influence of Seeding Rate

Godel (206, 207), working with cereals in Canada, suggested that higher than normal seeding rates of 2.5 to 3.6 bu/A may provide a practical weed control method in annual cereal crops.

In 1910 Montgomery (351) experimented with oats and reported that the percentage of plants tillering brought the stand up to normal at low seeding rates. At seeding rates of 12 to 16 pecks/A the number of tillers decreased, but yield decreased only at the highest seeding rates. In a 1909 corn experiment, Montgomery (350) found the yield of stover/A increased directly with planting rate, but grain yield remained unchanged when three to five seeds/hill were planted. At higher seeding rates, a greater proportion of barren stalks and smaller ears resulted. These results, while not particularly important today because they are so well known, are included to indicate how long this kind of information concerning crop plants has been known. However, the interaction of crop seeding rate and weeds does not enjoy equal historical treatment nor much attention in contemporary literature.

Staniforth and Weber (490) found increased soybean seeding rates reduced weed yield. Pfeiffer and Holmes (407) observed that an increased barley seeding rate, with no herbicide application, significantly reduced the yield of competing oats. They extrapolated these results (with no supporting data) to propose a possible solution to the *Avena fatua* problem in barley. Results reported by others do not support their solution (49, 74, 333, 363).

Mann and Barnes (322, 323), however, determined that barley seeding rate was a direct determinant of its success as a competitor. Another study (321) indicated that seeding rates in excess of 4 lb/A generally reduced yields of grain sorghum under dryland conditions in the state of California (USA). Plant population appeared to be a more important determinant of yield than row spacing.

Burrows and Olson (119) determined that increased wheat seeding rate enlarged yield from weedy plots, but not from plots either weeded by hand or sprayed with 2,4-D. They concluded that the minimum weed density justifying spraying depended on seeding rate. At 1 bu/A, the critical weed density was 5.5 wild mustard plants/ft². However, at 2 or 3 bu/A, the weed densities needed to justify spraying were 22 and 44 mustard plants/ft², respectively.

Increasing flax seeding rates from 42 to 70 lb/A (212, 213) moderated yield losses caused by competition with *Polygonum convolvulus*. The same relationship held true for sugarcane as planting density increased (128).

Seed size can also determine competitiveness. Black (58) studied the effects of seed size of subterranean clover under spaced and meadow conditions. Under spaced conditions of 1 plant/25 square links, dry weights throughout the season, and at harvest,

were nearly proportional to the initial seed weight of 3, 5, and 8 mg. When three seed weights in 3:6:12 ratio were planted under solid stand meadow conditions of 625 plants/m², dry weights were again proportional to seed weight early in the season. When a leaf area index of four was reached, a reduction in growth rate occurred, starting with the heaviest seed. Thus, growth rates differed, but at a leaf area index of four, dry weights equilibrated so that at harvest there was no difference in yield among the three seed weights. This experiment emphasizes the importance of interspecific competition.

Montgomery (350) studied two oat varieties and concluded that plants from a small-seeded variety endured a marked disadvantage. The yield decrease out-distanced the decrease in the number of plants, indicating a very rapid elimination of those plants having the inherited initial disadvantage in growth. Aspinall and Milthorpe (35) attributed barley's greater competitive ability with *Polygonum lapathifolium* to its larger seed embryo and significantly larger physical stature at emergence.

In other studies Black (57, 59) found that the extra advantage in embryonic capital of plants from large seeds resulted in a cumulative advantage in mixed culture over individuals from small seeds. At the end of 84 days of growth, the plants from small seeds were receiving only 2% of the incident light energy. Black credited the shading effect of large-seeded plants with the disappearance of small-seeded plants in mixed culture.

Black also compared seed size and ½, 1¼, and 2 inch planting depths with the preemergence and early vegetative growth of subterranean clover (57). All three depths of planting with the three seed sizes, decreased the weight of cotyledons at emergence. However, cotyledon weight has little influence on subsequent seedling growth, whereas cotyledon area does; the latter was constant at a given planting depth. He concluded that if emergence is realized, depth of planting is not critical. Also, in a plant with epigeal germination and no endosperm, seed size has importance for two reasons: (a) limitation placed on maximum hypocotyl elongation, hence, depth of planting; and, (b) seed size determines cotyledon area which, in turn, influences seedling growth. Said Black (58), "In an annual crop, early growth may be dependent upon, or proportional to, the weight of the seed, but there is no such relationship in total growth or final yield." Little information on the influence of seed size on weed crop interactions is available to correlate with the pasture studies.

C. The Influence of Tillage

In 1959 McKibben (332) said that annual tillage and cultivating operations in the U.S. involve the use of 4½ million farm tractors that supply 120 million horsepower. He further stated, "More than 250 billion tons of soil are turned or stirred each year, much of it several times, by tillage and cultivating operations. This is probably the world's largest materials-handling operation. It is enough soil to make a ridge 100 feet high and one mile wide from New York to San Francisco." Shaw and Loustalot (461) added the opinion that, "About one-half of this operation is practiced solely for the control of weeds."

The role of soil tillage, i.e., plowing, seedbed preparation, or crop cultivation, as a weed control method is well accepted. The importance of weed control through soil tillage is so well accepted it is recorded in weed science textbooks (22, 364). It is not the purpose of this paper to challenge this thinking, but it is interesting to note that the evidence is largely qualitative. There are detrimental effects of cultivation such as soil drying, increasing wind or water erosion, root pruning (435), and foliar damage, but the perception of benefits dominates current thinking.

The weed control aspect of cultivation has been documented in corn (518, 558), cotton and soybeans (518), cotton (83, 84), beans (124), and in small fruits and vegetables (428). Buchanan and Hiltbold (92) found no difference in cotton yield for various cultivation practices on two soils over a 3 to 5 year period. Cultivation resulted in yields equal to, but not greater than, those obtained from weed removal without soil disturbance. In short, there was little effect of cultivation beyond weed control.

Thurston (514) revealed that depth of seed burial is an important determinant of weed emergence and thus of weed problems in cereals. She proposed that the depth of final cultivation may determine weed problems by preventing or encouraging germination of certain species.

A negative linear relationship developed between emergence of seedlings of *Abutilon theophrasti*, *Polygonum aviculare*, *Setaria faberii*, and *Setaria lutescens* and physical resistance of soil (301). *A. theophrasti* had the highest emergence from compact soil and *P. aviculare* the lowest. There was no effect of depths between 0.5 and 2 inches in low resistance soils, but emergence declined rapidly with depth in high resistance soils. Emergence of *Chenopodium album*, *Asphodelus tenuifolius*, *Melilotus alba*, *Melilotus indica*, *Vicia hirsuta*, and *Angallis arvensis* suffered 90% reductions due to soil compaction, while perennials *Cirsium arvense*, *Cynodon*

dactylon, and *Cyperus rotundus* were virtually unaffected (465). Soil compaction did not depress wheat yield.

D. The Influence of Crop Sequence

Very few studies have focused on the influence of rotation or crop sequence on specific weed species or weed population extent. Rotations are assumed to affect weeds, but the knowledge is qualitative, not quantitative. Nalewaja (362) showed that spring wheat yield increased significantly when corn or soybeans were hand weeded and treated with herbicides the preceding year. The literature contains abundant evidence supporting the utility of winter wheat-fallow rotations for moisture conservation and increased wheat yield. Burnside et al. (109) advocated one-way tillage plus herbicides as the best method to control *Bromus tectorum*. They were able to show a three-fold reduction in weed stand for the one-way disc compared to the sweep plow. Moldboard plowing reduced weed stands even more, but did not sufficiently increase yield to justify its added cost. One winter fallow period reduced *Avena fatua* populations up to 97% and two consecutive fallow periods reduced density to less than 0.2 *A. fatua*/m². A third year provided no additional reduction (411).

Weed seed populations in soil supporting sugarbeets were appreciably lower following a bean crop than following either barley or corn, according to Dotzenko et al. (175). The rate and time of nitrogen fertilizer application significantly affected weed seed numbers. High nitrogen levels increased numbers of weed seeds.

In a 6-year Illinois study of herbicide use on two rotations including corn, soybeans, and wheat, Slife and Houghton (467) disclosed that soil weed seed numbers shrank considerably when weeds were well controlled.

E. Relationship Between Competition and Genotype

Although genotypes might be expected to influence the optimum seeding rate in a given community, and therefore competition, relatively little experimental evidence exists on the subject of agronomic crops.

Nelson and Ohlrogge (368) compared a spontaneous mutant Hy-1 dwarf corn with a normal Hy-2 corn hybrid. The Hy-2 normal

grain yield decreased 78% as population doubled from 26,000 to 52,000 plants/A. At the same time, the dwarf's yield fell by only 2%. In another study (475), similar results were explained by showing that all of the dwarf's growth after tasseling was expressed as an increase in ear weight, whereas, at high density the Hy normal continued to produce vegetative parts after tasseling.

Staniforth (481) found that late maturing corn hybrids were affected twice as much by *Setaria* spp. The greatest weed competition occurred in late summer, a period when early maturing hybrids had passed those growth cycle stages when weed competition could affect yield. These data reflect results similar to those reported by Smith (473) for competition of *Echinochloa crus-galli* in rice. A direct relationship emerged between time of maturation and competitive effectiveness.

The work of Lang et al. (308) provides additional information on density-genotype relationships. Several corn hybrids were grown at densities of 4,000 to 20,000 plants/A. At the lower densities, some hybrids produced many stalks and ears while others developed minimal branching or relatively few second ears. The former tended to be those with the lowest proportion of barren stalks at high densities. Hybrid plants with few stalks or second ears at low densities showed a high incidence of sterility in dense stands.

Hinson and Hanson (253) studied soybeans at spacings of 2 to 32 inches in rows spaced 38 inches apart and ascertained a relationship between genotype and yield. They concluded that closely spaced soybeans showed varying susceptibility to competition while at wide spacings the plants were more able to display their inherent capacity to exploit the environment. Response to photoperiod primarily determined competitive ability of the four genotypes (253). In another experiment (226), the competitive advantage in yield acquired by one of a competing pair of genotypes tended to be lost by the second genotype in a community system. Staniforth found no difference in the response of four cultivars of varying maturity to competition from a mixed population of *Setaria lutescens* and three annual broadleaf species (483).

McWhorter and Hartwig (337, 338) substantiated that six soybean cultivars did not respond equally to competition from *Sorghum halepense* and *Xanthium pensylvanicum*. *S. halepense* was a more vigorous competitor than *X. pensylvanicum*, but the general order of cultivar response to the two weeds was the same. Similar response variation was reported for ten cultivars in competition with *Setaria viridis* and *Amaranthus tuberculatos* in Nebraska (105, 106). Dowler and Parker (176) noted that cultivar,

weed control system, and year-to-year weather variations influenced the number and size of weeds at harvest. Other Nebraska studies verified that the competitive ability of ten sorghum hybrids differed (116, 476).

Ulrich (521) pinpointed a genetic and environmental variation among sugarbeet plants of the same variety in the absence of other competition. Beet root weight varied by 12.3%, sucrose levels by 14.4%.

No significant interaction developed between competitive ability and variety found among five sugarcane varieties. However, regression analysis indicated that two varieties possessed greater weed competition tolerance (29).

Appleby et al. (25) showed that yield reduction percentages tended to be greater when short wheat cultivars competed with *Lolium multiflorum*.

Time of planting and growth form were important determinants of competitive ability in three squash cultivars, according to Stilwell and Sweet (495). A vine type competed well when planted early while the semi-bush types competed best when planted late.

Harper (227), in a paper discussing factors controlling plant numbers, mentions a point to be considered when assessing the affect of genotype on community. He observes that responses to density in which plasticity rather than mortality is responsible for population control permit a wider range of genotypes to remain in the community. □

XII. Methodology

Extreme time constraints cause most readers of scientific literature to limit their attention to abstracts and conclusions. Rarely can papers be read in *toto* nor can the relationship between experimental methods, results, and conclusions be carefully analyzed. Conclusions are, of course, a proper focus, but often methods are prime determinants of the conclusions' validity. Competition studies are no exception to this generalization. Understanding results requires detailed examination of the methodology employed.

The Food and Agriculture Organization of the United Nations has published a manual containing basic information concerning how to conduct field evaluations of losses due to pests, and how to perform surveys of losses. The manual also provides specific information on techniques, apparatus, and special methods for studying a wide array of crop pests (196). A short article sets out the principles for conducting weed competition studies (158). Schreiber (445), in another publication, has described a technique for studying weed competition in forage establishment.

Harper (228) pointed out that agronomists are concerned with the description of factors that determine crop yield and an analysis of causes which relate effects to environmental changes. The literature supports the proposition that the vast majority of weed-crop competition studies have been descriptive and not very analytical. That is, agronomists have diligently described the results of weed competition, but have not been equally attentive to analyzing why observed effects occur *vis-a-vis* specific crop-weed interactions or environmental changes.

Dawson (155) enumerated three elements most studies have attempted to determine:

- the time of weed emergence that causes yield reductions;
- the crop growing season period when weeds are most injurious;
- the crop growing season period when weeds are relatively harmless.

By implication, most studies have aimed to determine the extent of yield reduction. As mentioned previously, Friesen (199 cited in

438) presented several other questions that can be asked about weed-crop competition.

Sagar (438) outlined five methods for studying weed-crop competition to answer the three questions posed by Dawson (155) as well as the more general concern, yield reduction. The five methods were:

1. the Friesen method;
2. survey;
3. screening;
4. logarithmic;
5. model systems.

Friesen's method, a commonly employed technique, involves keeping a crop weed-free, or permitting natural or specific densities of weeds to grow for pre-determined periods of time, and then determining yield reductions. Surveys compare weed-free plots or fields with others having varying degrees of weediness, usually from a single weed species. Screening methods have been utilized in the greenhouse to define the characteristics which endow weeds with a competitive advantage. The logarithmic technique may facilitate rapid assessment of weeds' impact on crops by logarithmically sowing weeds along a strip of crop. Though developed primarily for crop associations, model systems offer great promise. Work by deWit and Baeumer (164) describes a technique for growing crop and weed separately and mathematically analyzing data from periodic harvests to predict the outcome of competition.

Each method has advantages and disadvantages. Surveys, screening, and logarithmic methods are rapid; they should identify significant weed problems, as well as the most important densities or competitive situations, for additional detailed study.

In a brief paper, Peters (406) critiqued the two primary methods employed in most competition studies (that Sagar [438] defined as the Friesen method) and described the artifacts in each of these methods. The methods are:

- determine when competition begins by allowing weeds to grow from crop emergence for varying lengths of time;
- determine the length of required weed-free period for maximum yield by keeping the crop weed-free for varying periods after emergence and then permitting weed growth.

Weed emergence periods vary. If the emergence period is short—most plants emerging within a short time span—plants increase in size with time, but population size remains constant. For extended emergence periods (e.g., *Avena fatua*), more weed plants appear as

the season progresses while the early emerged plants continue to increase in size. Thus, at any one time, there will be plants of different ages with differing competitive abilities, a complicating factor. Another problem: determining the onset of competition unavoidably disturbs the soil and crop plants. The second method involves less soil disturbance, but some plant disturbance. Crops may also compensate for early weed removal by more rapid growth.

Peters (406) proposed a method that allowed growth of only weeds emerging within predetermined time periods. This technique, best suited for weeds with long emergence periods, would determine which fraction of a competing population proved most competitive. Peters' main point was that the methodology employed in competition studies unavoidably includes artifacts that should be considered when results are interpreted. He attempted to indicate some of the problems associated with precise quantitative interpretation of results based on imperfect methodology. In spite of these techniques' disadvantages, they have been—and will continue to be—widely used for competition studies. The procedures "work" and, as long as the disadvantages are known and artifacts recognized or controlled, they are valuable.

The best example of developing a mathematical model to study the entire process of competition between herbage plants rests in deWit's work (163, 166).

Hill and Shimamoto (251) classified competition between herbage plants into three groups:

1. **Compensatory:** gains and losses incurred by two components counterbalance leading to constant net productivity.
2. **Positive complete complementation:** the advantage gained by the stronger component is such that the mixture's performance matches that of the better monoculture.
3. **Positive over-complementation:** yield of the better monoculture is surpassed by the mixture.

They used a diallel arrangement for analyzing competition and employed the essential features of the deWit density replacement series. In a later paper, Hill (248) developed a theoretical model to identify conditions under which a 50:50 mixture could be expected to exceed the average of component monocultures or surpass the better monoculture. Hill's latest paper (249) proposes a model for competing pairs of individuals in binary mixtures.

Thomas (509) used a mathematical approach to fit parameters to deWit's model to permit testing the hypothesis that species compete for space, or what space contains. Breese and Hill (75) proposed that the general competitive ability of a species could be measured by its general vigor, sensitivity to competition, and

aggressiveness. A plant's reaction to competitive stress may be similar to its reaction to other environmental stresses, such as drought. Fischer and Miles (194) used theoretical mathematical analysis to determine that arranging crop plants in a square lattice produced maximum competitiveness.

No studies of weed-crop competition have employed this complexity of mathematical analysis. Weed competition studies have been conducted in a wide range of crops by agronomists, horticulturalists, and weed scientists, but not with the specific intent of mathematical description.

In 1972 Dew (160) used data from studies by Bell and Nalewaja (49, 50) and Bowden and Friesen (74) to develop a mathematical index of competition for *Avena fatua*. His index ranked crops in competitive ability; barley led the list followed by wheat, flax, and rape (160, 161, 162). Using weed density data and expected weed-free yield of the crop, he mathematically verified that competition for each of the crop-weed combinations was unique as well as independent of the estimated weed-free yield and cultural practices. Where potential weed-free conditions generated high yields, extensive losses occurred for a given density of *A. fatua*. Regression methods could predict yield losses associated with varying densities. For Dew's theory, the ratio of the regression coefficient over the intercept (b/a) equaled the competitive index (161).

Zakharenko (584) also developed a formula to calculate probable crop losses from *Avena* spp., or probable yield increases from herbicide use in wheat, peas, flax, and forage corn. Schweizer (450) worked out a linear equation to predict sugarbeet root yield reductions caused by specific densities of *Kochia scoparia*. His equation proved most accurate when there were less than 20 *K. scoparia*/30.5 m of row. At higher densities, a quadratic or cubic equation was a better predictor.

Chisaka (137) used an equation to predict the affect of *Echinochloa crus-galli* on rice yield. Factors included crop yield, weed plant density, the reciprocal of weed-free crop yield, and a measure of factors influencing competition. He emphasized the need to consider rice cultivar and density, time of weed emergence, and nitrogen fertility among those conditions bearing on competition. □

XIII.

Economic Analyses

Unquestionably a vast amount of evidence substantiates the ability of weeds to reduce crop yields and exert other detrimental effects on agricultural production. To justify scientific endeavors, the researcher often must answer two questions: what is the extent of the problem; and, secondly, what is the importance of the problem. While this review does not address the first question directly, the diversity of citations presented for one crop or one weed species supports the generally accepted proposition that weed problems are extensive. Holm et al. (258) have answered the first question for several of the world's worst weeds. Information provided in foregoing pages answers the second question for specific weed densities and periods of competition. However, while farmers may recognize the importance of knowing when a given weed density will reduce yield, there is far greater interest in information that suggests whether or not to implement weed control practices.

Help for answering that question can come from an ability to forecast crop yield losses caused by weed competition (137). If weed control is necessary, the next step involves determining how intensive a control program should be implemented based on costs, returns, or other factors. Maximum yield may not always be the ultimate goal. For many farmers around the world, reducing risk outweighs maximizing yield. Too, farming for many is a business wherein maximum profit becomes more important than maximum yield. Socio-economic endowments need to be evaluated as well as the biological components of weed-crop competition.

A 1965 USDA report for the decade 1950 to 1960 (3) contains the most frequently quoted estimate of monetary losses due to weeds. Annual losses in crop yield and quality and the costs of weed control in the U.S. amounted to an estimated \$5.1 billion. This value, an estimate or educated guess, has become enshrined in most weed science texts, including one of the most recent ones (22). While the estimate has not been proven wrong, changes in the values of crops and inputs then and now, as well as the methodology employed to arrive at the figure, make it suspect.

In 1967, weeds caused an estimated 8% loss of potential agricultural production (268). In the same year, Cramer (143) published a worldwide summary of monetary losses attributed to pests of all kinds in the world's major crops. He calculated that 9.7% of the potential yield of major crops was lost solely due to weeds. Parker and Fryer (392) used Cramer's data (143) and calculated that weeds alone eliminated 14.6% of the world's actual crop production.

A national soybean loss survey conducted in the U.S. in 1970 (23) found weed competition caused an estimated 3.3 bu/A yield reduction in the 28 states included. Weeds were responsible for a 12% crop loss, each year. Chandler (133) summarized other estimates indicating that weed competition in some U.S. southern states caused as high as 20% soybean yield loss. For the entire country, 5% was regarded as an optimistically low level of loss, except on perhaps half of the acreage that is most intensively farmed.

In Canada, Friesen and Shebeski (200) estimated the annual loss due to weeds in Manitoba grain fields at \$32.3 million for 1959. Renney and Bates (419) estimated losses due to weeds in British Columbia were \$72 to \$78 million dollars/year in 1969. This study showed that 38 to 42% of weed-caused yield losses in British Columbia were due to yield reduction of agricultural crops and livestock, increased insect and disease problems, dockage, harvest losses, and costs of control. If forest weeds were included, losses in yield and costs of control accounted for an additional 45 to 49% of total loss.

The most recent estimate of weed impact, by Parker and Fryer (392) in 1975, calculated that 11.5% of the world's major crops yield was lost due to weeds, an annual loss of 285,500,000 metric tons. Present worldwide inflation and the lack of a world or country data base for each crop make it unproductive to attempt still another estimate of world, region, or crop losses due to weed competition.

World literature concerning domestic or international food production leaves little doubt about the benefits of weed control. Weeds are ubiquitous and their effects on yield create enormous losses which must be borne by all consumers. While loss data are impressive and may justify research, they are but a first step toward answering the question of whether or not to instigate control or, as Ashford (34) phrased it, "Does the situation warrant application of a herbicide?" Ashford mentioned just one control technology, but his reasoning for the apparent inability or reluctance to answer the question is pertinent. Information needed, he said, included weed density, competitive ability of weed or weeds, susceptibility of crop to weed competition, and the consequence of

no weed control. In fact, weed scientists can answer these questions, but with general and often qualitative information. Ashford suggested that yield should not be used as the sole criterion. Crop value, cost of control, ease of harvest, storage costs, dockage, crop quality and marketability, weed population in succeeding years, and affect on disease and insect problems also needed to be considered. Answers to these questions are even more general and qualitative.

Dawson (153) separated costs of hand labor, mechanical control, chemical control, and yield losses for sugarbeets grown in the Northwest United States. In 1965, commercial weed control for sugarbeets cost \$75/A. Fifty dollars was spent for hand labor and zero for herbicides; escaped weeds still cost growers \$14/A (about 1 ton/A yield in 1965). Total costs could have been reduced to \$58/A by increasing mechanical control from \$11 to \$27/A, adding \$22/A in chemical control, and reducing hand labor to a late postemergence thinning/weeding. The net benefit of the best available control methodology was \$17/A. Dawson^a revised his figures to reflect changing costs and technology and found the commercial program cost \$138/A and the program employing the most effective modern techniques resulted in a net savings of \$65/A.

Anderson and McWhorter (20) combined data from two earlier studies (334, 335) with current data to show that 70% control of *Xanthium pensylvanicum* in soybeans was required to prevent losses due to excessive seed moisture (greater than 13%). Net return was \$63/ha with no *X. pensylvanicum* control and \$119/ha with 95% control. Yield reduction was nearly linear from approximately 50 to 100% control. Below 50% a curvilinear relationship became apparent. The authors proposed that, "the proportional reduction in yield as a result of *X. pensylvanicum* infestation was approximately linear," and that soybean yield increased about 6.1% for each 10% increase in weed control.

Wiese (562) found one *Descurainia pinnata*/ft² reduced winter wheat yield 10% in one year, 6% in a second year, but had no effect in a third very dry year when the average yield was only 9 bu/A. *D. pinnata* did not reduce yield if controlled with 2,4-D applied after tillering, but before vigorous growth began in the spring. Because Wiese's study was reported in 1965, the costs of control and crop value are now inaccurate, but the methodology is still useful. Wiese determined the effect of several weed densities on wheat yield and estimated a percentage yield loss. When these data were combined with potential wheat yield, cost of 2,4-D and its application, and the value of wheat, the potential profit or loss from

^aDawson, J. H. 1978. Unpublished data.

control of *D. pinnata* could be calculated. This information helped growers answer the 'should I control' question as tabulated in Table XX.

TABLE XX

Potential profit or loss from control of *Descurainia pinnata* in winter wheat (562).

Weed density/ft ²	Estimated yield reduction (%)	Potential wheat yield (bu/A)		
		10	20	40
		Profit or loss* (\$)		
¼	2.5	-1.18	-0.87	-0.25
½	5.0	-0.87	-0.25	1.00
1	10.0	-0.25	1.00	3.50
1	20.0	1.00	3.50	8.50
4	40.0	3.50	8.50	18.50

*Profit or loss = value of yield loss if weeds uncontrolled, minus spray cost. Wheat sale price = \$1.25/bu
2,4-D + application = \$1.50/A

With low yields, only high weed densities justified control. If a higher yield was expected, initiating weed control at lower weed densities became profitable. Yield and cost of control were the sole criteria used in this analysis. The other criteria suggested by Ashford (34), being more difficult to quantify, were omitted. Nevertheless, Wiese's analysis provides a useful example of converting research data to information of decision-making value to growers.

TABLE XXI

Probable yield loss caused by various densities of *Avena fatua* in barley, wheat, and flax (48).

<i>A. fatua</i> seedlings/yd ²	Yield reduction (bu/A)		
	barley	wheat	flax
10	1.6	1.5	2.0
40	2.7	3.5	5.0
70	4.9	5.2	6.3
100	6.0	5.4	6.9
130	6.2	7.3	7.4
160	3.1	8.7	7.5

Wiese and Shipley (566) developed equations to predict grain yield based on various levels of weed infestations in sorghum and

wheat. They found one *Amaranthus retroflexus*/ft of row reduced sorghum grain yield 48% and one *D. pinnata*/ft² reduced yield of a dryland wheat about 9%. Specific relationships were not reported.

Bell and Nalewaja (48) calculated the financial loss/A caused by various *A. fatua* densities in average yields of barley, wheat, and flax.^a Their data can be converted to show the probable yield loss (Table XXI).

By assigning current costs to control procedures and crop values growers can calculate profit potentials and answer the 'should I control' question considering costs and yields only.

These analyses are useful, but too few in number and too limited in scope because of insufficient data to extend analysis beyond consideration of control costs and crop values. □

^a Average yield: barley = 31.9 bu/A; wheat = 21.1 bu/A; flax = 9.5 bu/A.



XIV.

Studies of Weed Biology

Literature on crop-weed competition, with emphasis on agronomic crops, forms the basis for material presented in this review. The introductory sections discuss information concerning competition in the community and effects on individual plants. A segment of the literature surveyed related to the biology of individual weed species. While these were not weed-crop competition studies, they have relevance to anyone studying competition of particular weeds in crops. Therefore, the studies found (albeit an incomplete list) have been included as a second, separate bibliography entitled: **Some Studies of Weed Biology.** □

XV.

Conclusion

The overwhelming weight of evidence presented in the preceding sections undeniably affirms the facts that weed competition reduces crop yield and that weeds at a known density reduce yield over a predictable range when present for the entire growing season. To anyone who has considered weed-crop interactions, this is akin to proclaiming that the sky is blue and grass is green.

One of the original goals of this review was to establish a firmer economic base for appraising the effects of weed competition. The operative premise was that if the range of effects on yield of a specific weed, or weeds in general, could be determined for a crop, a more precise estimate of weed-caused loss could be obtained. Such information would be valuable to justify continuing weed research efforts and to plan future research programs.

This goal has not been achieved for two reasons. First, the great diversity of experimental designs employed in weed competition studies and the variability of results preclude precise loss estimates. Yield reductions in competition experiments vary and experiments often are not conducted over a sufficiently long period nor under a wide range of environmental conditions. Smith (470, 471) recognized and reported the variability in his 4-year study with rice and emphasized the need for repeating competition studies because of biological and environmental variability.

Secondly, results of competition studies are overwhelmingly location specific. Referring to site specificity, Appleby (24) in 1977 mentioned factors of irrigation, weather, fertility, and time of weed germination. His list could be expanded to include soil type, pH, other competing weeds, crop cultivar, tillage, and timeliness of cultural operations for an area. Although specific economic conclusions are unwarranted, no basis exists to deny the general conclusion that weeds are detrimental. The crop orientation of this review will permit interested individuals to extract data appropriate to their area.

In fact, the general effect of weeds on crops has been so well described that the emphasis on such descriptive studies should be reduced. In addition, the aforementioned fact that such studies usually are site specific lessens their universality. Scientists have

diligently described the result of weed competition, but have not been equally attentive to analyzing why observed effects occur for specific crop-weed interactions or environmental changes. The experiments by Oliver et al. (379), and Scott and Oliver (452) are cited as being among several examples that analyze why observed effects occur rather than merely describing the effects.

The great emphasis on describing competition results also has led to at least one erroneous impression which Appleby (24) has noted. It is nearly an axiom among weed scientists that the most severe competition occurs early and therefore early weed control is required. This generalization is not true. Data in Tables XIV and XV indicate that almost all crops will withstand weed competition for a period of weeks before weeding is needed and that required weed-free periods are really quite long. Early competition is important, but only when one or more environmental factors becomes limiting early in the season. Moreover, even if one environmental factor is deficient, competition will not occur unless plants interact. That is, if all plants in a community suffer the lack of a given factor, yet the environment of each plant is independent of its neighbors, there will be no competition (171).

The weed science community does not need many more data to show that X weeds/Y area reduce yield of a crop by Z, with two exceptions. As new weed species become dominant, their specific effects need to be determined. Secondly, it seems that weed scientists should develop and utilize competition data (appropriate to their regions) to justify their endeavors in economic terms. Weed scientists traditionally have operated as though everyone knew weeds were a problem. They have failed to use available data, or generate new data, to vigorously stress the monetary importance of weeds, terms which everyone understands.

Weeds will always be present. They lack the drama and publicity of sudden and severe outbreaks of disease or insects. Weed scientists know this. Others do not. Competition data are indispensable for the educational process.

Beyond the important but crude economic reason for producing and using competition data, there lies an important reason for suggesting a halt to further routine competition studies. Attention now can be appropriately and more profitably (in the non-monetary sense) devoted to studies in two, more fundamental areas: weed biology and weed ecology.

This is neither a new nor radical position. Staniforth (484) suggested these areas in a brief paper in 1964. Harper (229) and, more recently, Sagar and Mortimer (439) have been strong advocates of such studies. Harper has already been quoted extensively, but his words bear repeating. "The essential qualities which deter-

mine the ecology of a species may only be detected by studying the reaction of its individuals to their neighbors and the behavior of individuals of the species in isolation may be largely irrelevant to understanding their behavior in the community" (229). Harper specifically intended "to focus attention on the reaction of a plant to its neighbors as a critical, often the most critical, part of the autecology of a species and to suggest that this type of study has a cementing and unifying function in the science of plant ecology."

Fourteen years later Sagar and Mortimer (439) discussed the population dynamics of plants with special reference to weeds. They stated that to comprehend population regulation is a primary aim of population biology, and actuarial data are necessary to understand demographic behavior. They explored two synoptic hypothesis to explain the behavior of plant populations. After forty pages of exploration, they reluctantly concluded they were unable to precisely identify the regulators of populations "in the necessary sense of density" related agents (439). They summarized that no general conclusions could be drawn and species would have to be examined separately.

The approach of those who work on biological weed control was presented as an attractive paradigm. This view suggests populations generally expand in new edaphic or climatic environments because of escape from a predator or pathogen. Therefore, regulation of population size may be from agents acting from above in the food chain rather than through limits of resources from below (439). The recent and increasing interest in shifts in weed populations and development of herbicide resistance in formerly susceptible species is evidence of the credence of this view.

The fact remains that plant populations are regulated. A reasonably sound understanding exists of how man achieves regulation, whether by chemical, cultural, mechanical, or biological means. But society lacks a thorough understanding of how organisms behave in their home (484). Weeds appear much more adapted to conditions in the world than crops and, because of the fine record of weed scientists, weeds have achieved some credibility in the halls of academia. Thus, it is a propitious time to focus attention on the more difficult, but potentially much more beneficial, question of how and why weed crop competition occurs and how and why the respective populations are regulated. □

XVI.

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XVII.

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□

XVIII.

Indexes

A. INDEX OF CROP PLANT SCIENTIFIC AND COMMON NAMES.

Scientific name	Common name
<i>Allium cepa</i> L.	garden onion
<i>Allium sativum</i> L.	garlic
<i>Arachis hypogaea</i> L.	peanut - groundnut
<i>Avena sativa</i> L.	oats
<i>Beta vulgaris</i> L.	table beet/sugarbeet
<i>Brassica campestris</i> L.	rape
<i>Brassica oleracea</i> (L.) var. <i>acephala</i>	kale
<i>Brassica oleracea</i> (L.) var. <i>botrytis</i>	broccoli
<i>Brassica oleracea</i> (L.) var. <i>capitata</i> L.	cabbage
<i>Cajanus cajan</i> (indicus)	common pigeon pea
<i>Citrus aurantium</i> L.	sour orange
<i>Cucumis sativus</i> L.	common cucumber
<i>Cucurbita pepo</i> L.	common pumpkin
<i>Cucurbita</i> spp.	squash
<i>Dactylis glomerata</i> L.	orchardgrass
<i>Daucus carota</i> (L.) var. <i>sativa</i> D.C.	garden carrot
<i>Discorea alata</i>	yam
<i>Festuca elatior</i> L.	meadow fescue
<i>Fragaria chiloensis</i> (L.) Duch.	strawberry
<i>Glycine javanica</i>	
<i>Glycine max</i> Merr.	soybean, soyabean
<i>Gossypium hirsutum</i> L.	cotton
<i>Helianthus annuus</i> L.	sunflower
<i>Hibiscus esculentus</i> L.	okra
<i>Hordeum vulgare</i> L.	barley
<i>Ilex crenata</i> Thunb	Japanese holly
<i>Lactuca sativa</i> L.	lettuce
<i>Lespedeza</i> spp.	lespedeza
<i>Linum usitatissimum</i> L.	flax
<i>Lolium multiflorum</i> Lam.	Italian ryegrass
<i>Lolium perenne</i> L.	perennial ryegrass

Scientific name	Common name
<i>Lotus corniculatus</i> L.	birdsfoot trefoil
<i>Lycopersicon esculentum</i> Mill.	tomato
<i>Malus pyrus</i> L.	apple
<i>Medicago sativa</i> L.	alfalfa
<i>Narcissus</i> spp.	narcissus
<i>Oryza sativa</i> L.	rice
<i>Panicum maximum</i> Jacq.	panicum, green panic, guinea-grass
<i>Phaseolus aureus</i> Roxb.	Mung bean
<i>Phaseolus vulgaris</i> L.	bean
<i>Phleum pratense</i> L.	common timothy
<i>Pisum sativum</i> L.	garden pea
<i>Poa pratensis</i> L.	Kentucky bluegrass
<i>Rubus idaeus</i> L.	raspberry
<i>Saccharum officinarum</i> L.	sugarcane
<i>Secale cereale</i> L.	rye
<i>Solanum tuberosum</i> L.	potato
<i>Sorghum bicolor</i> (L.) Moench	sorghum/milo
<i>Sorghum caffrorum</i> (a var. of <i>S. bicolor</i>)	Kafir
<i>Trifolium pratense</i> L.	medium red clover
<i>Trifolium repens</i> L.	white clover
<i>Trifolium subterraneum</i> L.	subterranean clover
<i>Triticum aestivum</i> L.	wheat
<i>Vicia faba</i> L.	field bean/broad bean
<i>Vicia sativa</i> L.	common vetch
<i>Vicia</i> spp.	vetch
<i>Zea mays</i> L.	corn/maize

□

B. INDEX OF WEED SCIENTIFIC AND COMMON NAMES*

Scientific name	Common name
<i>Abutilon theophrasti</i> Medic	velvetleaf
<i>Acnida altissima</i> Riddell	
—now <i>Amaranthus tuberculatos</i> (Moq.) J. Sauer	tall waterhemp
<i>Aeschynomene virginica</i> (L.) B.S.P.	northern jointvetch
<i>Agropyron repens</i> (L.) Beauv.	quackgrass
<i>Agrostemma githago</i> L.	corn cockle
<i>Agrostis alba</i> L.	redtop
<i>Agrostis gigantea</i> Roth	black bentgrass
<i>Agrostis</i> spp.	bentgrass
<i>Allium vineale</i> L.	wild garlic
<i>Alopecurus myosuroides</i> Huds	blackgrass/Pacific meadow foxtail
<i>Amaranthus hybridus</i> L.	smooth pigweed
<i>Amaranthus palmerii</i> S. Wats	Palmer amaranth
<i>Amaranthus powellii</i> S. Wats	Powell amaranth
<i>Amaranthus retroflexus</i> L.	redroot pigweed
<i>Amaranthus</i> spp.	pigweed
<i>Amaranthus tuberculatos</i> (Moq.) J. Sauer	tall waterhemp
<i>Amsinckia intermedia</i> Fisch & May	coast fiddleneck
<i>Angallis arvensis</i> L.	scarlet pimpernel
<i>Anoda cristata</i> (L.) Schlecht	spurred anoda
<i>Anthemis cotula</i> L.	mayweed
<i>Asphodelus tenuifolius</i> Cav.	
<i>Atriplex patula</i> L.	spreading orach
<i>Avena fatua</i> L.	wild oat
<i>Brassica arvensis</i> (L.) Rabenh	ball mustard
<i>Brassica campestris</i> L.	wild turnip
<i>Brassica hirta</i> Moench	white mustard
<i>Brassica kaber</i> (D.C.) L.C. Wheeler var. <i>pinnatifida</i> (Stokes) L.C. Wheeler	wild mustard
<i>Brassica</i> spp.	mustard
<i>Bromus catharticus</i> Vahl	rescuegrass
<i>Bromus inermis</i> Leyss.	smooth brome
<i>Bromus secalinus</i> L.	cheat
<i>Bromus tectorum</i> L.	downy brome
<i>Capsella bursa-pastoris</i> (L.) Medic.	shepherdspurse

*Names from: Composite List of Weeds, 1971. Weed Sci. 19: 437-476.

Scientific name	Common name
<i>Cassia obtusifolia</i> L.	sicklepod
<i>Chenopodium album</i> L.	lambsquarters
<i>Chondrilla juncea</i> L.	rush skeletonweed
<i>Chorispora tenella</i> (Willd.) D.C.	blue mustard
<i>Cirsium arvense</i> (L.) Scop.	Canada thistle
<i>Convolvulus arvensis</i> L.	field bindweed
<i>Cynodon dactylon</i> (L.) Pers.	Bermudagrass
<i>Cyperus difformis</i> L.	smallflowered umbrellaplant
<i>Cyperus esculentus</i> L.	yellow nutsedge
<i>Cyperus rotundus</i> L.	purple nutsedge
<i>Cyperus</i> spp.	nutsedge
<i>Dactylis glomerata</i> L.	orchardgrass
<i>Dactyloctenium aegyptium</i> (L.) Richter	crowfootgrass
<i>Descurania pinnata</i> (Walt.) Britt	tansy mustard
<i>Desmodium tortuosum</i> (S.W.) D.C.	Florida beggarweed
<i>Digitaria sanguinalis</i> (L.) Scop.	large crabgrass
<i>Echinochloa colonum</i> (L.) Link	junglerice
<i>Echinochloa crus-galli</i> (L.) Beauv.	barnyardgrass
<i>Eichhornia crassipes</i> (Mart.) Solms	water hyacinth
<i>Eleusine indica</i> (L.) Gaertn	goosegrass
<i>Emex australis</i> Steinh	emex, three cornered jack
<i>Fagopyrum tataricum</i> (L.) Gaertn	Tartary buckwheat
<i>Festuca arundinacea</i> Schreb.	reed or alta fescue
<i>Galeopsis</i> spp.	
<i>Galeopsis tetrahit</i> L.	hempnettle
<i>Galinsoga parviflora</i> Cav.	smallflower galinsoga
<i>Heteranthera limosa</i> (Sw.) Willds.	ducksalad
<i>Hibiscus trionum</i> L.	venice mallow
<i>Holcus mollis</i> L.	german velvetgrass
<i>Hordeum murinum</i> L.	wall barley
<i>Impatiens parviflora</i> DC.	snapweed
<i>Ipomoea hederacea</i> (L.) Jacq.	ivyleaf morningglory
<i>Ipomoea purpurea</i> (L.) Roth.	tall morningglory
<i>Kochia scoparia</i> (L.) Schrad.	kochia
<i>Lappula echinata</i> Gilib	european sticktight
<i>Lepidium campestre</i> (L.) R.Br.	field pepperweed
<i>Lepidium intermedium</i> Gray	pepperweed
<i>Lolium multiflorum</i> Lam.	italian ryegrass/Darnel

Scientific name	Common name
<i>Lolium perenne</i> L.	perennial ryegrass
<i>Lolium rigidum</i> Gard	persian ryegrass
<i>Lychnis alba</i> Mill.	white cockle
<i>Matricaria inodora</i> L.	scentless mayweed
<i>Medicago</i> spp.	annual medic
<i>Melilotus alba</i> Desr.	white sweetclover
<i>Melilotus indica</i> (L.) All	annual yellow sweetclover
<i>Melilotus</i> spp.	sweetclover
<i>Mollugo verticillata</i> L.	carpetweed
<i>Monochoria vaginalis</i> (Burm, F.) Presl.	monochoria
<i>Nicandra physalodes</i> (L.) Pers.	apple-of-Peru
<i>Panicum dichtomiflorum</i> Michx.	fall panicum
<i>Panicum maximum</i> Jacq.	guineagrass
<i>Panicum repens</i> L.	torpedograss
<i>Paspalum fasciculatum</i> Wild.	bamboograss
<i>Phalaris minor</i> Retz.	littleseed canarygrass
<i>Poa annua</i> L.	annual bluegrass
<i>Polygonum aviculare</i> L.	prostrate knotweed
<i>Polygonum convolvulus</i> L.	wild buckwheat
<i>Polygonum lapathifolium</i> L.	pale smartweed/white persicaria
<i>Polygonum nepalense</i> Meissn.	
<i>Polygonum pennsylvanicum</i> L.	Pennsylvania smartweed
<i>Polygonum persicaria</i> L.	ladysthumb
<i>Portulaca oleraceae</i> L.	common purslane
<i>Portulaca</i> spp.	purslane
<i>Richardia scabra</i> L.	Florida pusley
<i>Rottboellia exaltata</i> L.	itchgrass
<i>Salsola kali</i> (L.) var. <i>tenuifolia</i> Tausch	Russian thistle
<i>Sapnaria vaccaria</i> L.—see, <i>Vaccaria segetalis</i>	cow cockle
<i>Schedonnardus paniculatus</i> (Nutt.) Trel.	tumblegrass
<i>Senecio vulgaris</i> L.	common groundsel
<i>Sesbania exaltata</i> (Raf.) Cory	hemp sesbania
<i>Setaria faberii</i> Herrm.	giant foxtail
<i>Setaria italica</i> (L.) Beauv.	foxtail millet
<i>Setaria lutescens</i> (Weigel) Hubb.	yellow foxtail
<i>Setaria</i> spp.	foxtail
<i>Setaria viridis</i> (L.) Beauv.	green foxtail
<i>Sida spinosa</i> L.	prickly sida
<i>Sinapsis arvensis</i> L.—see, <i>Brassica kaber</i>	wild mustard

Scientific name	Common name
<i>Solanum rostratum</i> Dunal	buffalobur
<i>Solanum sarachoides</i> Sendt.	hairy nightshade
<i>Solidago nemoralis</i> Ait.	gray goldenrod
<i>Sorghum bicolor</i> (L.) Moench	shattercane
<i>Sorghum halepense</i> (L.) Pers.	johnsongrass
<i>Spargula arvensis</i> L.	corn spurry
<i>Stellaria media</i> (L.) Cyrillo	chickweed
<i>Thlaspi arvense</i> L.	field pennycress
<i>Tripleurospermum maritimum</i> (L.) Koch—row, <i>Matricaria</i> <i>maritima</i> L. var. <i>agrestis</i> (Knaf) Wilmott	false chamomile
<i>Typha augustifolia</i> L.	narrowleaf cattail
<i>Veronica agrestis</i> L.	field speedwell
<i>Veronica persica</i> Poir.	birdseye speedwell
<i>Vicia hirsuta</i> (L.) S.F. Gray	ting vetch
<i>Viola arvensis</i> Murr.	field violet
<i>Xanthium pensylvanicum</i> Wallr.	common cocklebur
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□

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D. CONVERSION TABLE FOR UNITS USED IN THE TEXT

<u>to convert</u>	<u>into</u>	<u>multiply by</u>
Acre	hectare	0.4047
Acre	square feet	43,560.0
Acre	square meters	4,047.0
Bushel*	cubic feet	1.2445
Bushel	cubic meters	0.03524
Bushel	liters	35.24
Bushel	hectoliters	0.3524
Bushels/Acre*		
Centimeter	feet	3.281×10^{-2}
Centimeter	inches	0.3937
Centimeter	meters	0.01
Centimeter	millimeters	10.0
Centimeter	yards	1.094×10^{-2}
Feet (Foot)	centimeters	30.48
Feet (Foot)	meters	0.3048
Feet (Foot)	millimeters	304.8
Feet (Foot)	yards	.333
Gram	kilogram	0.001
Gram	milligram	1000.0
Gram	pounds	2.205×10^{-3}
Hectare	acres	2.471
Hectare	square feet	1.076×10^5
Inches	centimeters	2.540
Inches	meters	2.540×10^{-2}
Inches	millimeters	25.40
Inches	yards	2.778×10^{-2}
Kilogram	grams	1000.0
Kilogram	pounds	2.205
Kilograms/hectare	pounds/acre	0.892
Links	inches	7.92
Meters	centimeters	100.0
Meters	feet	3.281
Meters	inches	39.37
Meters	millimeters	1000.0
Meters	yards	1.094
Milligrams	grams	0.001

*Bushel is a volume measure and therefore a bushel of one grain may not weigh the same as another. Usually accepted bushel weights are:

barley - 48 pounds
 corn - 56 pounds
 sorghum - 56 pounds
 soybeans - 60 pounds
 wheat - 60 pounds

Milliliters	liters	0.001
Millimeters	centimeters	0.1
Millimeters	feet	3.281×10^{-3}
Millimeters	inches	0.03937
Millimeters	meters	0.001
Millimeters	yards	1.094×10^{-3}
Pounds/acre	kilograms/hectare	1.12
Square feet	acres	2.296×10^{-5}
Square feet	square inches	144
Square feet	square meters	0.09290
Square feet	square yards	0.1111
Square meters	acres	2.471×10^{-4}
Square meters	square centimeters	10^4
Square meters	square feet	10.765
Square meters	square inches	1550.0
Square meters	square yards	1.196
Square yards	acres	2.066×10^{-4}
Square yards	square centimeters	8,361.0
Square yards	square feet	9.0
Square yards	square inches	1,296.0
Square yards	square meters	0.8361
Yards	centimeters	91.44
Yards	meters	0.9144
Yards	millimeters	914.4

□

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