Considerations in Introducing Foreign Biotic Agents to Control Native Weeds of Rangelands[1]

by
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ABSTRACT

The most serious weeds of rangelands in the southwestern United States are native plants that have increased greatly in abundance under past management systems. Biological control offers the promise of low cost, effective, and permanent control by the introduction of biotic suppressant from the same or closely related plant species native to similar climatic zones, principally in southern South America. Since introduced suppressants attack all plants of the weed species, we must consider possible damage to beneficial uses of the weed, the effects of removing native weeds from the ecosystem, and man's possible need for the weed in the future. The development of methods to minimize possible harmful effects can be included in an introductory program. We need to evaluate the success potential for biological control of a weed and its beneficial and harmful effects. Then the various weeds can be ranked in order of their overall potential for biological control.——

Today we are witnessing an increased interest in biological control of weeds. This has been stimulated by several recent successes in biological control; by recent increases in fuel and labor costs, which have increased the cost of herbicides and mechanical controls; by the increasing demand for higher agricultural productivity and the need to utilize marginally productive areas; and because some of the more effective herbicides with long residual effects are limited in usage although they have not been proven harmful.

Biological control of weeds has had a history of considerable success. Of 41 projects attempted throughout the world in the last 80 years, 75% have achieved a measurable degree of success; 8 were rated as completely successful (no further controls needed), 9 gave substantial, and 14 partial control (DeBach 1974, Sailer 1975). Attempts at biological control of rangeland weeds so far have been concentrated on weeds of the western and northwestern areas of the U. S. and of southern Canada, especially on introduced weeds. Successful projects have been completed or are in progress to control several serious weeds in these areas such as St. Johnswort (*Hypericum perforatum* L.) Russian thistle (*Salsola* sp.) puncturevine (*Tribulus terrestris* L.) tansy ragwort (*Senecio jacobaea* L.) and several thistles (*Carduus* spp., *Centaurea* spp., *Silybum* spp.) (Holloway 1964, Andres and Goeden 1971).

Severe weed problems also exist on rangelands and pastures in the southern Great Plains and semi-arid southwestern areas of the U. S. (Fig. 1). More than 80% of 107 million acres of grazing land in Texas alone is infested with brush (Klingman 1970). Range weeds in this area have never been objects of serious attempts at biological control. A few introduced weeds have become serious problems in limited areas, for example, African rue (*Peganum harmala* L.) McCartney rose (*Rosa bracteata* Wendl.), and saltcedar (*Tamarix* spp.), but the most serious and widespread pests are native species. Many of these are toxic to livestock in addition to being competitors with forage grasses. Also, woody species hinder the handling of livestock and hinder range improvement efforts such as seeding.

Several native species of brush and herbaceous weeds are important weed problems in Texas and other southwestern states (Smith and Rechenthin 1964, Sperry *et al.* 1965) Chief among the brush species are mesquite (*Prosopis* spp.), whitebrush (*Aloysia* spp.), shin oak, live oak, and post oak (*Quercus* spp.) huisache (*Acacia farnesiana* (L.) Willd.), Texas persimmon (*Diospyros texana* Scheele), juniper (*Juniperus* spp.), creosotebush (*Larrea divaricata* Cav.), tarbush (*Flourensia cernua* DC.), yaupon (*Ilex vomitoria* Ait.), blackbrush (*Acacia rigidula* Benth.), sagebrush (*Arte-*

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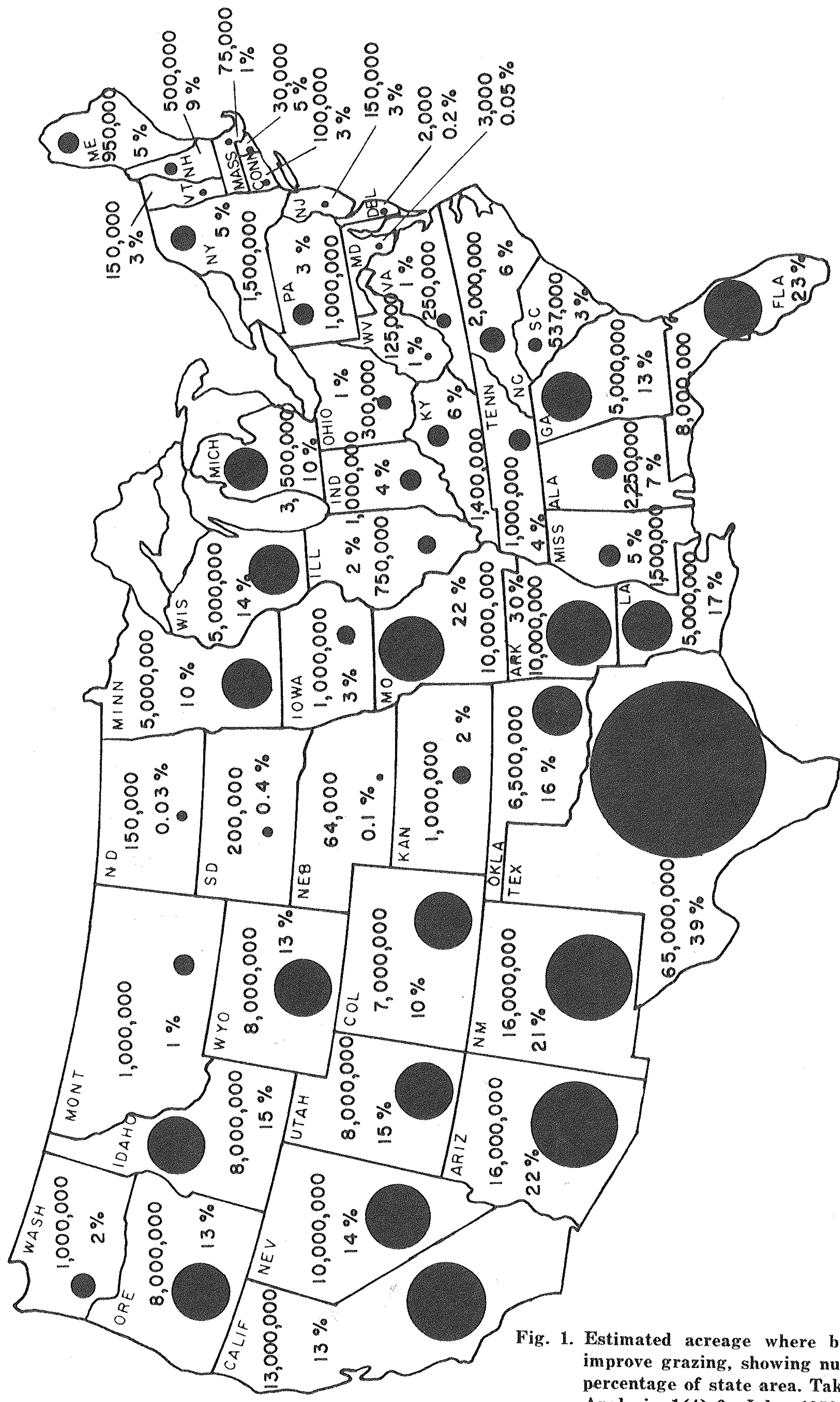

Fig. 1. Estimated acreage where brush removal can improve grazing, showing number of acres and percentage of state area. Taken from Armour's Analysis 1(4):3, July, 1952 (from Klingman 1970).

misia spp.) retama (*Parkinsonia aculeata* L.), and cactus (*Opuntia* spp.) The herbaceous weeds of most importance are broomweed (*Gutierrezia*), ragweed (*Ambrosia* spp.), the goldenweeds (*Isocoma* spp.), *Ericameria* sp., bitterweed (*Hymenoxys odorata* DC.), smutgrass (*Sporobolus indicus* (L.) R.Br.), groundsel (*Senecio* spp.), locoweed (*Astragalus* spp.), and nightshade (*Solanum* spp.).

Several of these native weeds have increased enormously in density over the last 120 years. In spite of considerable efforts in the last 20 years to control them by chemical and mechanical means, the area infested and requiring treatment has remained unchanged. However, recent efforts using new chemical and mechanical controls have reduced the density. The early settlers in the Southwest reported that luxuriant native grasses covered most of the plains areas, with mesquite and other brush growing along streams and in the draws; today mesquite and other brush and weeds cover most of the area. Other species such as huisache and retama appear to have extended their natural range from northern Mexico into southern and central Texas. For example, in 1858, mesquite occupied only 5% of a southern New Mexico range but had increased to 50% by 1963; tarbush increased from 1 to 9% during the same period (Klingman 1970). This increase in density and spread of weeds is the result of a change from the natural system of periodic grazing by buffalo to the present system of constant grazing by cattle and sheep. Overgrazing, drought, spread of seed by livestock, and reduction of range fires have all contributed to the increase of brush and weeds (Smith and Rechenthin 1964, Klingman 1970, Scifres 1973).

Biological control is ideally suited to control of weeds and brush in rangelands, where the major weed pests are perennials growing in a relatively undisturbed habitat, and where the low economic return per hectare makes chemical and mechanical control expensive. However, biological control alone may not be appropriate against some weeds and may give less control than desired against others. The limitations of its use were recently discussed by Frick (1974b) and include situations where eradication of the weed is needed, where important conflicts of interest exist in the use of the weed, or where the target weed is widely scattered within a vegetation complex.

Morrow *et al.* (1962) found that chemical control of brush in Texas produced a benefit-cost ratio of 3.14 for post oak-blackjack in eastern Texas and 2.30 for mesquite in west Texas (1.0 is the break-even point). They also reported that in mixed brush areas of southern Texas the benefit-cost ratio for rootplowing and reseeding was 3.72, for chaining was 3.15, for roller chopping was 2.13, and for treedozing was 3.34. Brown *et al.* (1974) made an economic analysis of chaparral conversion to grassland in Arizona. By selecting only the most productive 27% of the land in the study area, and applying the optimum combination of chemical and mechanical treatments and burning, benefit-cost ratios varied from 0.1 to 6.4; benefit-cost ratios were 0.1 to 1.0 on 16% of the area, 1.0-2.0 on 30%, 2.0-3.0 on 37%, and greater than 3.0 on 17% of the area.

The total research program for biological control of a weed species (by the introduction of foreign suppressants) averages 1-2 million dollars at current prices (Andres, in press), which is relatively inexpensive compared with other methods. Andres (in press), in summarizing several recent successful projects on biological control of weeds, reported benefit-cost ratios up to 200:1 and even to 1000:1. The major reason that biological control is less expensive is that the biological suppressants spread naturally from a few release sites, become permanently established, and exert a constant pressure on the weed, whereas chemical or mechanical controls must be applied periodically to the entire infested area.

In this paper, I will discuss the advantages and limitations of various methods of biological control of native weeds, factors that influence our chances of success in finding effective biotic suppressants, factors that must be considered in ranking target weeds in order of priority for research and control, conflicts between the beneficial vs. harmful effects of the weed, and possible adverse effects on the ecosystem.

GENERAL APPROACHES

Augmentation.—Two general approaches are available to biological control of weeds. The first is to increase the effectiveness of biotic suppressants already present in the ecosystem. Methods of augmentation, manipulation of the agro-ecosystem, and conservation that can be used were recently reviewed by Frick (1974a), Andres (1971), DeBach (1971), and Sailer (1975). Augmentation is equally appropriate for use with introduced or native weeds or with introduced or native suppressants that are less effective than desired. The method has the advantage that it can be applied only in specific areas and can be discontinued altogether if necessary; therefore, the method poses little or no danger to beneficial uses of the plant. Disadvantages are that the method nearly always requires a constant input of energy and therefore is costly. However, plant pathogens may be much cheaper to mass produce and to use "bio-herbicides" than would insects or other organisms. Augmentation may be practical in crops with a high value per acre, but in situations such as rangelands where the value per acre is low, it probably is not economical.

Introduction of foreign biotic suppressants.—The second general approach is the introduction of foreign biotic suppressants, usually insects, though mites, nematodes, plant pathogens, or other organisms have been or may be used. This method has the advantage of being self sustaining, cheap, and permanent. Under ideal conditions the insects are released in the field, increase on their own (except possibly for some initial dispersal by man to speed up control), and give control with no further input of effort or energy. Ideally, the only cost is that of the research to find and test the proper control agents.

The introduction of foreign biotic suppressants historically has been used mostly with introduced weeds, but the method can also be used to control native weeds (Wilson 1964, Andres 1971). Only three cases, one planned and two accidental, have been reported to date whereby a native weed was controlled by an introduced foreign suppressant. Prickly pear cactus (*Opuntia* spp.) is a native on Santa Cruz Island, California; a scale (*Dactlopius opuntiae* Cockerell) was introduced from Mexico via Australia and Hawaii in 1951 and by 1967 had eliminated most of the weed (Goeden *et al.* 1967). Manuka weed (*Leptospermum scoparium* J. R. and G. Forster) was controlled in New Zealand in the 1940's by a mealybug (*Eriococcus orariensis* Hoy) that was accidentally introduced from Australia (Hoy 1961). Bermuda cedar (*Juniperus bermudiana* L.) was greatly reduced in Bermuda by the accidental introduction of two scale insects (Wilson 1964). Another promising case is that of an Argentine thrips that is being studied in Canada for possible release against ragweed (*Ambrosia* spp.) (Harris[3], personal communication).

Several beneficial native plants have been destroyed or damaged by the accidental introduction of harmful foreign organisms. Examples are the chestnut and the American elm by introduced pathogens and insects from related plant species in Europe and grapes in France by the grape phylloxera (*Phylloxera vitifoliae* (Fitch)) from North America. The ecological principles are the same with the plants we call weeds. These examples demonstrate that excellent control of native weeds is possible wth foreign organisms that evolved on different but related plant species.

SEARCH FOR FOREIGN SUPPESSANTS

Historically, two general principles have been followed in finding effective foreign suppressants: (1) search near the site of origin of the weed, and (2) search in areas with a climate similar to that where the weed occurs in the U.S. (Wilson 1964). The chances of finding an effective, safe suppressant are greatest with introduced weeds that do not have close relatives in North America. The chances for success decrease as (1) we try to control native weeds and weeds that have close beneficial relatives in the country where control is desired, (2) we are forced to look for suppressants on plants more and more distantly related to the target weed, and (3) we look in climatic areas different from that where control is desired.

At site of origin of weed.—To find an effective suppressant, we should, if possible, first look near the area where the plant evolved. Locating the site of origin of a plant species or genus is not an easy matter, and as man introduces plants from one area of the world to another it becomes even more difficult. The site of origin of the genus is usually defined as the region with most genetic diversity within a species, usually with the greatest number of species, and where forms with the lowest number of chromosomes are found. Occasional exceptions may occur where a species evolved that has fewer chromosomes than the ancestral type or where a genus underwent a burst of speciation as it entered a new region or habitat (Burson[4], personal communication).

Several situations from the point of view of the site or origin of the weed species and genus influence the chances of success:

(1) The site of origin of the weed genus is in another region of the world, and our weed species is also native there. The chances of finding an effective biotic control agent should be excellent.

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Creosotebush and whitebrush are examples among rangeland weeds.

Creosotebush (the genus *Larrea*) seems to have originated in western Argentina, where 4 species have evolved (Palacios and Hunziker 1972). One of these is probably the same as our *Larrea divaricata* Cav., which is the only species occurring in North America.

Another weed that may have originated in the same area is whitebrush (the genus *Aloysia*). Thirty species of *Aloysia* occur in southern South America but only 8 in Mexico and the U.S. (Correll and Johnston 1970, Troncoso 1974). Our most important species, *Aloysia lycioides* Cham., is probably synonymous with the South American *Aloysia gratissima* (Gill. and Hook.) Troncoso.

(2) The site of origin of the weed genus is another region of the world, but our weed species does not occur there. Although we must search on other species of the genus, the chances of finding useful suppressants are still good. Examples of rangeland weeds in this category are mesquite and baccharis.

Mesquite (the genus *Prosopis*) is represented by only 5 species in the United States and Mexico (Johnston 1962). Since no natural barriers exist between the U.S. and Mexico, it is likely that any organisms that evolved on Mexican species of mesquite have already migrated to the U.S. if they can survive our climate or can develop on our species of mesquite. Therefore, looking in Mexico for suppressants is not promising unless we intend using them in an augmentation program.

The genus *Prosopis* apparently originated in southern South America (Burkart 1940); however, none of the North American species of mesquite are indigenous to that area. Some 25 species of *Prosopis* have evolved in southern South America with a variety of forms and ecological adaptations. We expect a variability among the insects and other organisms living on *Prosopis* corresponding to the great variability among the plants.

The genus *Baccharisa* apparently originated in southern Brazil where over 100 species have evolved. About 20 species occur in the U.S. and a few more in Mexico; 11 species occur in Texas (Correll and Johnston 1970).

(3) The site of origin of the weed genus is North America, but several species also occur naturally in other regions of the world. In some cases more species may exist in other areas than occur in North America. The chances of success are still good if sufficient genetic variability exists and species can be found that are similar to our species.

An example is broomweed (the genus *Gutierrezia*). The most primitive species is the North American *Gutierrizia sarothrae* (Pursh) Britt. and Rusby, which has a diploid $2N=2X=8$ chromosomes or base number $X=4$. This indicates that the genus originated here and later spread to southern South America where it speciated greatly in the new habitat. Solbrig (1960, 1963, 1966) lists 8 species in North America and 11 in Argentina, Chile, and Bolivia; all the South American species are high polyploids of the base number $X=4$.

(4) The weed genus originated in another region of the world (not North America), but many species later spread naturally to other areas including the U.S. We must search for suppressants on different plant species in another region that is not the site of origin of the genus (we may be prevented from searching near the site of origin because of costs or because the area is politically inaccessible).

An example is loco weed. The genus *Astragalus* probably originated in northern Asia (Good 1974), but 368 species are native in the U.S. (Barneby 1964) and 87 species are native in temperate South America (Johnston 1947). This number of species is enough to offer good possibilities of finding suppressants that do not occur in the U.S.

Senecio presents a slightly different situation. It is probably the largest and the most truly cosmopolitan of all plant genera (Good 1974). A serious problem species in west Texas is *Senecio longilobus* Benth., which is native. We might be able to find suppressants in many areas of the world with similar climates. More than 400 species of *Senecio* occur in southern South America (Good 1974) and insects are known there that severely damage some of them. Other insects are known that damage *Senecio* in Europe.

In similar climatic areas.—Second, we should look in areas of the world that have a climate similar to the climate where the weed grows in the U.S. The rangeland weeds with which we are concerned occur in the hot, arid areas of the southwestern U.S. from central Texas across New Mexico and Arizona to California and into central Mexico. The range of a few species extends further north to Canada.

A climatic area remarkably similar to that in the southwestern U.S. exists in western and northwestern Argentina, northern Chile, southern Bolivia, Paraguay, and southern Brazil, centering in the "Monte" and "Chaco" brush areas (Fig. 2). Many of the most important rangeland weeds in the southwestern U.S. originated in this area or have close relatives or counterparts there. This disjunction between the same or similar species in the Chihuahuan and Sonoran deserts of the U.S. and Mexico and the similar climatic zones of northern Argentina and Chile is an interesting botanical phenomenon. The flora and fauna of both areas have been extensively compared in recent years (Morello 1958, Solbrig 1872a, b).

The scant data available indicates that most of the insect species on rangeland weeds in South America differ from those on the same weeds in the U.S. We, therefore, have a good chance of finding effective suppressants in southern South America.

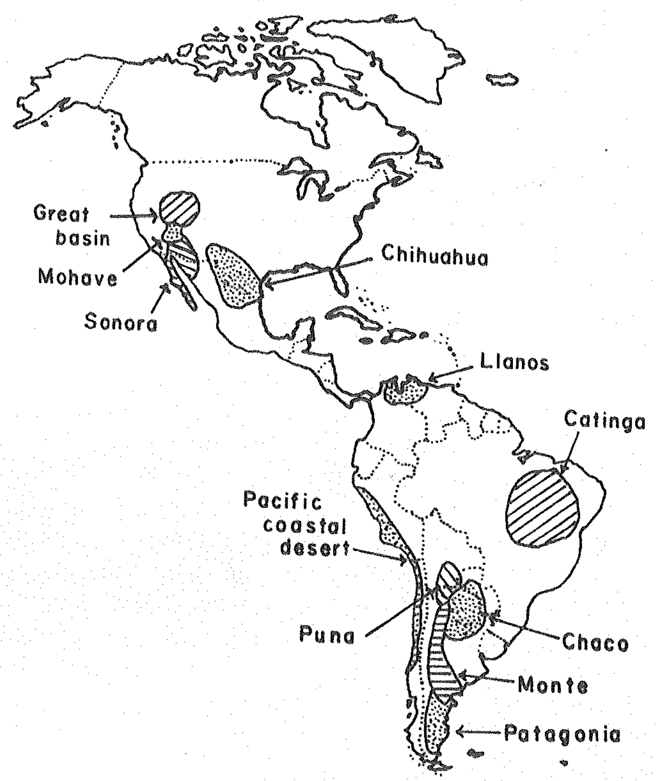

Fig. 2. Map showing the approximate area of the major semi-desert areas of North and South America (from Solbrig 1972b).

SAFETY OF INTRODUCED FOREIGN SUPPRESSANTS

The introduction of foreign biotic suppressants has met with great success in the past, and careful testing has prevented the introduction of organisms that might cause damage to beneficial plants. However, the method has certain inherent risks (Huffaker 1959, and 1964, Wilson 1964, Sailer 1975), and plans to avoid or overcome them should be made early in a research program. Some of these risks are more serious with native than with introduced weeds.

Danger to crops.—The introduction of foreign boitic suppressants involves some slight risk that the introduced organisms may also attack benefiicial plants or crops (Huffaker 1959, Wilson 1964). This risk necessitates very careful testing of the host range of the candidate organism in the country of origin, or in strict quarantine in the country of planned release, before the organism is released in the field. The theory and methodology of this testing has been highly refined (Zwölfer and Harris 1971). Wilson (1964) stated that, "No errors have been made and none should be made. The indications are that excessive anxiety has been felt about the matter of risks . . . ". Also, the slight risk involved must be weighed against the known enormous damage caused by weeds and the high cost of their control.

Conflicts of interest between benefiicial uses and harmful effects of the weed.—The usefulness or harmfulness of any given weed may be a matter of controversy (Huffaker 1959 and 1964). For example, ranchers who are attempting to maximize livestock production would like ranges devoid of any plants except nutritious palatable forage plants and enough trees for shade for the livestock. Other ranchers who have income from deer (or other wild game) hunting as well as from raising cattle want a properly balanced mixture of good forage plants for the cattle and areas of cover and browse for the deer. This cover might be oak, persimmon, whitebrush, or even mesquite. Also, honey producers are heavily dependent on whitebrush and huisache, and homeowners utilize mesquite and to a lesser extent retama, huisache and other brush species for ornamentals and shade trees over a wide area of the southwestern U.S. If we introduce an insect that devastates mesquite trees, the homeowner's shade trees will also be damaged or killed. If we control certain weeds, such as creosotebush, and the ranchers continue to overgraze as they often have, we could create enormous erosion problems.

On the other hand, we cannot refuse to try to control weeds that seriously reduce livestock production on ranges, knowing the desperate need to produce the maximum amount of food possible for the world's increasing human population.

Most conflicts between beneficial and harmful aspects of a weed may be resolved by assigning monetary values to them. Whether or not to initiate control might be largely decided by a cost-benefit analysis: the projected gains in production and savings on present control methods, less the value of any damage caused to beneficial uses of the weed and the cost of the biological control program.

"Compromise" control measures are possible that would minimize damage to the beneficial uses of the plant. For example, insects might be introduced that would attack only the seed or the very young plants, thus limiting the spread of a weed but not harming existing plants that are used as ornamentals, for honey production, etc. Insects might be introduced that are known to produce only moderate damage or damage only at certain times of the year. Such insects might cause the weed to succumb to competition from other plants in natural or range conditions but not where the plant was protected from competition as an ornamental. Also, chemical or other controls could be developed for an insect before it is introduced that could be used to protect desirable plants.

A "turn-on:turn-off" method has recently been proposed by Vogt and Cordo (In press) whereby foreign suppressants are introduced from the tropics. Since these organisms cannot overwinter here, they can be discontinued if they prove harmful. The method would, of course, involve the cost of annual introduction, and dispersion.

Possible upset of the ecosystem.—Control of introduced weeds is unlikely to upset any ecological balances because the plant is an invader of the natural system anyway; presumably little or no ecological harm will be done by removing it. However, any native plant is part of an intricate web of dozens or hundreds of organisms, all interdependent in various ways. Some of these relationships are understood but most are not well known and can be discovered only after long and careful study. We know that the system is very elastic, but the removal of any plant, especially one of the dominant species, will have drastic effects on at least a few other organisms.

A few examples of possible ecological benefits of weeds, aside from the direct economic values we must consider, include:

(1) Production of nesting sites, seeds or insects for food, and protection for a variety of wildlife species

(2) A place to live for beneficial insects

(3) Alternate hosts for insects or pathogens that attack other weeds

(4) Alternate sources of host insects for predators or parasitoids that attack insect pests.

Careful ecological studies are needed to determine the place of the weed in the food chain and as a place to live for the many organisms that depend on it in whole or in part for their existence. In the future, we will probably need to estimate the amount of control we expect to produce and to assess the major effects of this control on the ecosystem before releases are made.

Man's changing needs.—Our agro-ecosystem and many other aspects of our lives are rapidly changing, as the human population increases and fuel and mineral resources are depleted throughout the world. We cannot accurately predict what our future needs will be, and some of the plants we now consider as noxious weeds may become beneficial plants in the future.

Many species of animals and plants have become rare, endangered, or extinct. It seems certain that this trend will continue in most of the world. Indeed, as the human population increases, we may not be able to concern ourselves about endangered species or recreational values or anything else except maximum production of human food. It is also possible that if we greatly disrupt the ecosystem to maximize food production we may destroy some critical element that will allow the buildup of plagues that will devour our crops. We must therefore live in the present and do what is possible to increase food production now, but we must also leave as many options open for the future as possible.

The introduction of foreign suppressants is usually thought to have a permanent effect on the weed and on the ecosystem, but this effect may not be irreversible. This effect can probably be reduced or eliminated in the future if our changing needs require production of the former weed as a beneficial plant. Nearly all phytophagous insects have their own set of natural enemies in their region of origin, and these probably can be introduced later to control the phytophagous insects. Much past experience has shown that introducing parasites of insect pests is a very safe procedure, though it may not always be successful.

EVALUATION OF CANDIDATE WEEDS FOR BIOLOGICAL CONTROL

The two major needs for making research on biological control of weeds more efficient are to develop objective, logical systems for selecting (1) which are the most appropriate weeds for research, and (2) which are the most appropriate organisms to introduce to control the weeds. A system for selecting the most effective control agents was recently proposed by Harris (1973), but no systematic approach has been developed for selecting or assigning a priority ranking to target weeds. Such a system requires the analysis of a large amount of information on widely divergent aspects such as the harmful effects and beneficial uses of the weed, the effects on the ecosystem if the weed is removed, the potential for achieving successful control, the cost of and benefits to be derived from control, the integration of biological with other control methods, and public acceptance of control programs. Such analyses are important before beginning a program of biological control of any weed but are especially important for native weeds. Unfortunately, thorough pre-release studies have rarely been made in the past because they are difficult and time consuming and the urgency of the problem usually demanded that actual control should begin as soon as possible.

DeBach (1971), in discussing biological control of insects, argued that the ultimate success of a given candidate for introduction *cannot be predicted in advance,* but that we can find and select good risks. He stated that the only practical method of obtaining the best natural enemy is through multiple introductions of all promising candidates. Competition after release will then select for the most effective species, and that anyway, there is generally no single best natural enemy throughout the range of a pest species. He further argues that from a practical standpoint, long-term basic ecological research need not precede importation of new natural enemies of a pest species; any delay in discovery and importation of an effective natural enemy merely lengthens the time that a species remains a pest.

Whatever the merits of this argument, a system of evaluation is more important for biological control of weeds than of insects though the ecological principles that DeBach discusses may apply to biological control of all pests. Parasites of insects may be introduced with little prior research and at very little risk, but introducing weed suppressants involves much additional safety testing. We *must* determine in advance at least that they will not attack crops or other beneficial plants. This additional testing, usually 2-4 years in a foreign location for each suppressant, means that a suppressant for weeds is generally much more expensive than one for insects. The many urgent weed problems and the limited funds and personnel available to study them demand that some selection of projects be made so that the most promising and the most important should be attempted first, and also that the most promising suppressant should be introduced first.

Insufficient information is available at the present time to make an adequate evaluation of most rangeland weeds, but we have a reasonably good idea of the factors that should be considered. Other factors might be added or changes made as the system is refined.

Success potential for biological control of a weed.—Much of the information needed to evaluate the chances for successful biological control of a weed is available, although information about some factors will require research. The intensity and type of attack by native organisms on the candidate weed in the U.S. at present requires considerable study. These studies may reveal weak points in the present control system, for example, the absence of stem borers or seed feeders, and we could then search specifically for organisms in other regions to fill this empty niche. Conversely, the presence of an abundant organism in the U.S. that already causes much damage might prevent the establishment or reduce the effectiveness of an introduced ecological counterpart. Factors that should be considered in evaluating the success potential are:

(1) Whether the weed is introduced or native

(2) Whether the weed is annual or perennial

(3) Whether the weed is a pest in stable or in disturbed habitats

(4) Site of origin of the weed genus

(5) Number of species of the weed genus in the U.S. and at the site of origin

(6) Number and importance of cultivated or valuable wild plant species closely related to the weed

(7) Known insects in other countries that regulate weed density

(8) Previous successful biological control attempts on the weed species

(9) Intensity and type of attack by enemies in U.S.

(10) Estimate of the amount of control that can be produced by the proposed biological agents

(11) Ease of control by chemical, mechanical or cultural means

(12) Degree of control required

Damage caused by weeds.—Rangeland weeds cause losses mainly by reducing the forage available for grazing by competing for moisture, light, and nutrients, by making the management of livestock difficult, and by direct toxicity to livestock. A reasonably accurate estimate of these losses is very important to any cost-benefit analysis designed to evaluate which controls are most practicable and which weeds are most important to control. However, this type of information is very difficult to obtain and may require expensive, large scale experiments and surveys. Much work has been done on the ecology and control of some weeds, especially mesquite (Schuster 1969, Scifres 1973) and accurate experimental information is available on the amount of forage production that is lost at various densities of several weeds (Bovey *et al.* 1972, Dahl *et al.* 1974). However, more information is needed on such things as pounds of beef (or lamb or wool) lost per acre and on actual losses sustained by producers over a wide area.

In order to make decisions on what type of control programs should be initiated, we need to know how much increased production will actually occur if the weed is controlled. We assume that if we remove mesquite, creosotebush, broomweed, or other major range weeds that we will greatly increase forage production and the amount of livestock products we can produce. We need more data to evaluate how much benefit might actually result, taking into account the production potential of each area. Measuring the area of infestation and density of any one species such as mesquite with any reasonable degree of accuracy is an enormous undertaking in itself; however, remote sensing with satellite or aerial photographs offers a potentially important breakthrough. A reasonably accurate measurement of the area infested and density is essential both before release and after release of biotic suppressants to measure the control produced. Such measurements may be required over a 10-15 year period, and should be accurate enough to detect a small reduction in weed density.

Direct losses of livestock by eating poisonous plants are also difficult to measure and more information is needed. Dollahite[5] (personal communication) estimated that losses were $118,000,000 annually in the Great Plains area and that up to 40% of a calf crop may be lost by abortions if the brood cows eat broomweed, *Senecio,* loco weed, or other poinsonous plants. The rancher must observe all brood cows carefully and frequently to know which ones have aborted, a task that is nearly impossible on large ranges covered with brush.

Increased costs of management, or losses incurred because of a lack of management, are perhaps the most difficult to measure. On ranges covered with dense stands of brush, livestock is difficult to observe or to round up for medical treatment or for other purposes.

The principal factors that should be evaluated in estimating losses are:

(1) Area infested
(2) Density within the infested area
(3) Potential for spread or increase in abundance
(4) Losses caused at various weed densities
(5) Value and potential productivity of the land occupied
(6) Toxicity to livestock
(7) Toxicity or allergencity to humans
(8) Damage to recreational areas
(9) Loss of runoff or soil water
(10) Present and future cost of control by chemical or mechanical means.

Beneficial values of weeds.—Probably even less is known about the beneficial values of weeds than about their harmful effects, and again, such information is difficult to obtain. Surveys could measure the use of various weeds as ornamentals, but the assignment of monetary values to the aesthetic qualities is rather arbitrary. Large field experiments under different grazing pressures probably would be necessary to measure the value of such weeds as creosotebush for erosion control. Surveys or experiments can also be devised to measure other beneficial values but considerable effort is required to obtain reliable data. Factors that should be measured are the value of the weeds as:

(1) Ornamentals
(2) Wildlife food or cover
(3) Aesthetic value in parks or wilderness areas
(4) Erosion control
(5) Honey production
(6) Feed or supplementary grazing for livestock
(7) Human food
(8) Fuel, lumber, pulpwood, fiber, etc.
(9) Source of medicines, drugs or other chemicals.

Modeling approach to weed control.—Recent advances in modeling offer an efficient, systematic, and logical method of evaluating many of the factors listed above and their ramifications for a biological control program (Arkin[6], personal communication). Models might be used to help decide (1) whether biological, chemical, or mechanical control, grazing management systems, prescribed burning, or some combination of these would provide the optimum control for a given weed, (2)

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to evaluate the socio-political impact and public acceptance of various control systems, (3) to establish and compare benefit-cost ratios for alternative systems and to provide a sound basis for resolving conflicts of interest between harmful and beneficial values of the weed, (4) to assist in deciding whether augmentation of native suppressants or the introduction of foreign suppressants would be best, and (5) to help decide how much control and what means of attack on the plant would be most effective and acceptable. Models could then help to determine which weeds are most important to control and to establish a priority ranking of weeds for biological control efforts. Available data from land resource management studies and other research information can be used in a modeling approach. More information will undoubtedly be needed on several factors before satisfactory decisions can be reached, and the models can also be used to pin-point where information is deficient.

CONCLUSIONS

Brush and other noxious weeds infest vast areas of rangelands in the southwestern United States and cause enormous losses to the livestock industry. The most serious pests are native plants that have increased greatly in abundance under past management systems. Present controls for many of these weeds are ineffective, expensive, and nonselective. Biological control by the introduction of biotic suppressants (mostly insects or plant pathogens) from foreign regions offers the promise of effective, permanent, and relatively inexpensive control for several of the most important weed species.

The project on rangeland weeds is one of the largest and most difficult biological control projects ever attempted. Several major brush and herbaceous weed species require control and each may require the introduction of several suppressants. For controlling native weeds, we cannot use the classical approach of returning to the site of origin of the weed and introducing the enemies that control them there. Instead, we must search for suppressants on closely related plant species in foreign regions, with consequent reduced chances of success. Also, many of the weeds have at least minor beneficial values. Therefore, and we must consider the impact of introduced suppressants on the beneficial uses of the weed species and on the ecosystem if the native weeds would be greatly reduced in abundance.

Nevertheless, according to the criteria discussed on climatic affinity and the site of origin of the weed genus, we conclude that good possibilities exist for finding effective suppressants on several of the more important range weeds. The introduced African rue is an excellent candidate for biological control and we also have good chances of finding effective suppressants for several native weeds that have close relatives in southern South America, for example, creosotebush, whitebrush, mesquite, baccharis, broomweed, loco weed, *Senecio* and others.

Other factors than the chance of finding an effective suppressant influence whether a weed is a good candidate for biological control. By these criteria, several important range weeds appear to be unpromising candidates. However, they should not be eliminated from all consideration because present information is incomplete and more intensive study might show that effective, safe control is possible. For example, some range weeds are very closely related to beneficial plants in their respective genera and a suppressant with an unusually high degree of host specificity would be required to insure that those beneficial plants would not also be attacked. Examples are the introduced McCartney rose and the native oaks, junipers, yaupon, persimmon, and the nightshades. Other weeds may have too much beneficial value themselves for us to introduce foreign suppressants that would probably attack all plants of the species whether it grows as a weed or is used as a beneficial plant; examples are the introduced saltcedar and the native prickly cactus.

A biological control program on rangeland weeds, especially of native weeds, should evaluate the amount of damage caused, the beneficial values, and the success potential for biological control of candidate weeds. With this information we can select the most effective general method of control for each weed and the best weed species for biological control attempts. Such a project will require the cooperation of entomologists, plant pathologists, plant ecologists, plant and insect taxonomists, range scientists, agricultural economists, socio-political scientists, modelers, and others. It will require careful ecological studies of the weed and the agro-ecosystem in the U.S. and careful exploration and testing overseas.

All methods of control should be considered, including preventive, cultural, chemical, mechanical, and biological, and no method should be thought of as the only solution. Even if biological control is only partially effective, it can become part of an integrated control program (Frick, 1974b). Promising weed and brush control methods have been developed during the past 20 years (Reardon and Merrill, 1976; Scifres, 1973). Even partial suppression of a weed by biological agents might give control desired when combined with these other methods.

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