BIOLOGICAL CONTROLS AS COMPONENTS OF INTEGRATED WEED MANAGEMENT FOR RICE IN THE UNITED STATES

Roy J. Smith, Jr.
Agricultural Research Service
U.S. Department of Agriculture,
Stuttgart, Arkansas, U.S.A.

ABSTRACT

Biological weed control practices have demonstrated their benefits for weed control in rice (Oryza sativa L.) when integrated into weed and pest management programs. Several biological weed control strategies, including microbial herbicides and wild ducks, are used commercially in rice while other strategies, including insects and natural products, have been successful only experimentally. Although only a few biological control practices are available for weed control in rice, compared with chemical herbicides and cultural and mechanical practices, it is evident that biological control strategies will require integration with all weed and pest management programs to be a viable component of a pest management system for rice. Research will be the key to development and integration of useful biological weed control strategies for rice.

INTRODUCTION

Integrated pest management for crops is a concept that combines pest control principles, practices, materials, and strategies to maintain plant health by minimizing damage from pests (Kendrick 1988, Shaw 1982, 1984). Components of integrated pest management systems vary according to the presence of different modifying factors. Strategies include minimum use of chemical pesticides to maintain pests below economic thresholds, use of biological control agents for specific pests, use of resistant crop cultivars, modification of cultural practices to prevent or reduce pest infestations, and the use of any input to prevent the deleterious impact of pests on crops.

Integrated weed management is a viable component of integrated pest management (Shaw 1982, 1984; Smith 1982). The weed management system combines use of multiple-pest-resistant, high-yield, well-adapted crop cultivars, that also resist weed competition, with precise placement and timing of fertilizers to give the crop a competitive advantage. Optimum crop plant population, the use of crop cultivars that form a canopy for shading early-season weed growth, and seedbed tillage and seeding methods that enhance crop growth while minimizing weed growth, are viable components of the system. Such systems also include the use of judicious irrigation practices; timely and appropriate cultivation; carefully planned crop rotations; field sanitation; harvesting methods that do not spread weed seeds; use of biological control agents and strategies, such as pathogens, insects, nematodes, animals, and allelopathy; and employment of effective chemical weed control methods. Also, preventive weed control practices to reduce the number of weed seeds and other propagules in the soil are a component of the system.

Many of the elements needed for effective integrated weed management systems are currently limited or unavailable (McWhorter 1984, McWhorter and Shaw 1982, 1984, Watson 1992). Some important needs include plant pathogens and insects to control weeds selectively, highly competitive cultivars, cultivars that are highly tolerant to herbicides and their residues, and information on chemical and biological interactions

Key words: Biological weed control, integrated weed control, microbial herbicides, mycoherbicides, rice, weed control

that occur between the pesticides and the living organisms used in the crop production system.

Although weed control technology integrates preventive, cultural, mechanical, chemical, and biological practices, the use of herbicides is probably the most important component of the weed management system for most major crops produced in the United States (Hill 1982, McWhorter 1984, McWhorter and Shaw 1982, 1984, Smith 1982). Because more than 140 herbicides are now available for control of weeds in cropping systems (Anon. 1989), numerous herbicide programs that combine preplant, preemergence, and postemergence treatments are available for control of important weeds in most crops. In contrast, only two microbial herbicides are registered for use on crops in the United States: an endemic fungal pathogen, *Colletotrichum gloeosporioides* (Penz.) Sacc f. sp. *aeschynomene* (*C.g.a.*) for control of northern jointvetch [*Aeschynomene virginica* (L.) B.S.P.] in rice (COLLEGO[3,4]) and a soil-borne fungus, *Phytophthora palmivora* (Butler) Butler for control of stranglervine [*Morrenia ordorata* (H. & A.) Lindl.] in citrus groves in Florida (DeVine[5]) (Charudattan 1991, Smith 1991). For example in Arkansas in 1992, 11 chemical herbicides and only one microbial herbicide were recommended for weed control in rice (Anon. 1992a). Consequently, chemical herbicides are combined into numerous tank mixtures and sequential treatments to control complexes of weeds in rice. COLLEGO, however, is limited to only a few combinations because tank mixtures of COLLEGO and some chemical herbicides and pesticides used in rice inhibit the germination and growth of the pathogen (Klerk 1983, Klerk *et al.* 1985).

Several microbial herbicides have been developed for control of weeds. The mycoherbicide LUBAO is commercially used in China to control parasitic dodder (*Cuscuta* sp.) in soybean (*Glycine max* L.) (Templeton 1992). It is a strain of *Colletotrichum gloeosporioides* that was discovered in 1963, and by the late 1970s was being applied to 670,000 ha of soybean in 10 provinces giving 85% control of dodder. BIOMAL is a mycoherbicide being developed by PhilomBios in Saskatoon, Saskatchewan, Canada, for control of round-leaf mallow (*Malva pusilla* Sm.) in wheat (*Triticum aestivum* L.) and other crops of the prairie provinces of Canada and the northern plain states of the United States (Templeton 1992). A dry formulation of the fungus *Colletotrichum gloeosporioides* f. sp. *malvae*, it was being marketed in Canada in 1992, with marketing planned in the United States for 1993.

Other biological strategies for weed control in rice include wild ducks (Smith and Sullivan 1980), insects (Oraze and Grigarick 1992), and rice that contains natural products or allelochemicals (Dilday *et al.* 1991). In Arkansas, farmers flood rice fields during the winter to attract wild ducks for feeding on red rice seed. This strategy reduces the number of red rice seeds in the soil and benefits subsequent rice crops. In California, aphids controlled some aquatic weeds selectively in rice. Although rice germplasm has been identified which contains allelochemicals that reduce aquatic weeds such as ducksalad [*Heteranthera limosa* (Sw.) Willd.], this strategy is not used commercially. Development of rice cultivars with allelopathic properties will require transfer of this trait from rice germplasm to desirable cultivars through conventional breeding or biotechnology techniques (Toenniessen 1990).

The purpose of this paper is to discuss the integration of biological control methods, including microbial herbicides, into weed control and pest management programs in rice production systems. Emphasis is on interactions of COLLEGO and chemical herbicides, fungicides, and insecticides.

DISCUSSION

Integrated Use of COLLEGO for Weed Management in Rice

A disease of northern jointvetch was discovered in 1969 at the University of Arkansas Rice Research and Extension Center at Stuttgart, in field plot experiments conducted to determine the interference of northern jointvetch on rice (Smith 1986 & 1991). The pathogen, *C.g.a.*, infected and killed weed seedlings in preliminary growth chamber, greenhouse, and field experiments. Host range research indicated that the fungus infected and killed only northern jointvetch in rice field environments of the southern United States.

Small-plot replicated field experiments and

---

[3] *C.g.a.* is commercially available as COLLEGO from Ecogen Corp., Langhorne, PA.

[4] The use of trade names in this publication does not constitute a guarantee, warranty, or endorsement of the products by the U.S. Department of Agriculture or the Arkansas Agricultural Experiment Station.

[5] Commercially available as DeVine from Abbott Laboratories, Long Grove, IL.

aerial applications of *C.g.a.* to flooded rice fields in nonreplicated field trials developed precise and accurate information on times, rates, volumes, methods of application, water management, and crop production practices (Smith 1986). Although in early experiments and field trials, wet spore preparations controlled northern jointvetch, dry-formulations of *C.g.a.* developed by industry also consistently controlled northern jointvetch in rice trials. Pilot tests in commercial rice field environments were conducted under experimental use permits granted by the U.S. Environmental Protection Agency (EPA). During this period, research and development involved scientists and technical people in industry working in close cooperation while they developed a suitable dry-formulated product, defined registration requirements with EPA, assessed market potential, and conducted required safety tests. After all the data on efficacy, pathogen biology, and toxicology data of *C.g.a.* had been assembled in a coherent document, the scientists involved managed to develop a marketable two-component product. This consisted of dry-formulated spores and a fungal spore-rehydrating agent (a sugar solution). EPA granted a conditional registration for COLLEGO in June 1982, and following submission of additional data, EPA granted full registration in October 1982 (Bowers 1986). This first commercially registered mycoherbicide for use on an annual weed in an annual agronomic crop was applied to farmers' rice fields in 1982. During the 10 years (1982-1991) that COLLEGO has been available, farmers have treated 5,000 to 10,000 hectares of rice annually.

Intensive research was conducted on the integration of COLLEGO with chemical herbicides, fungicides, and insecticides, separately and in various combinations. Many chemical pesticides applied in tank mixtures or sequentially with COLLEGO inhibit *C.g.a.* infection and control of northern jointvetch, while others applied in specific management programs have had a synergistic effect or no effect on *C.g.a.* activity. Consequently, interactions between chemical pesticides and plant pathogens with a microbial herbicide range from enhancement to suppression of disease incidence.

Tank mixture treatments of *C.g.a.* with the herbicides propanil[6], 2,4,5-T, and the fungicides benomyl or fentin hydroxide, inhibited fungal infection of northern jointvetch (Klerk 1983). Propanil, 2,4,5-T, fentin hydroxide, and benomyl, however, applied a few days after *C.g.a.* treatments did not inhibit disease infection and development. Likewise, the insecticides malathion and carbofuran or the herbicides aciflurofen or bentazon applied in tank mixtures or sequential treatments with *C.g.a.* did not inhibit infection or disease development on the weed.

Recommended chemical herbicides, fungicides, and insecticides can be applied in a program with COLLEGO without having an adverse interaction with *C.g.a.* For example, sequential treatments of recommended chemical herbicides (including propanil, molinate, thiobencarb, pendimethalin, fenoxaprop, 2,4-D, bentazon, triclopyr, and bromoxynil) and COLLEGO do not inhibit activity of *C.g.a.* on northern jointvetch. Indeed, a tank mixture of COLLEGO and acifluorfen is recommended for control of northern jointvetch and hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. ex A.W. Hill] complexes in rice (Anon. 1992a).

Recommended fungicides, including benomyl, iprodione, and propiconaszole (Anon. 1992b) can be applied sequentially with COLLEGO without adversely affecting *C.g.a.* activity on northern jointvetch. Likewise, recommended insecticides including carbaryl, carbofuran, malathion, and methyl parathion (Anon. 1990), can be applied sequentially with COLLEGO without reducing the activity of *C.g.a.* on northern jointvetch.

Adverse interactions between COLLEGO and chemical herbicides, fungicides, and insecticides used for rice have been prevented by using a computerized system based on accumulated heat units (degree-days at a base temperature of 10°C) to time application of COLLEGO and chemical pesticides (Huey 1987). After the farmer supplies information on the rice cultivar and the date of rice emergence, the program returns information to the farmer on many production inputs as well as on timing sequences for applying COLLEGO with chemical herbicides, fungicides, and insecticides.

A constraint of COLLEGO is that it controls only northern jointvetch, while most chemical herbicides control several weeds. This limitation can be overcome by applying a mixture of pathogens to mixed weed populations. For example, the rice weeds northern jointvetch and winged waterprimrose (*Ludwigia decurrens* Walt.) were controlled by applying a mixture of *C.g.a.* and *Colletotrichum gloeosporioides* f. sp. *jussiaeae* (Boyette *et al.* 1979). Similarly, a mixture of these two pathogens along with *C. malvarum* effectively controlled northern jointvetch, winged waterprimrose, and prickly sida

---

[6] Chemical names of pesticides are presented in Table 1.

Table 1. List of pesticides with common and chemical names, and classification

Common name	Chemical name	Classification
Acifluorfen	5-{2-chloro-4-(trifluoromethyl) phenoxy]-2-nitrobenzoic acid	H
Atrazine	6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine	H
Benymyl	methyl 1-(butylcarbamoyl)-2-benzimidazolecarbamate	F
Bensulfuron methyl	methyl 2-[[[[[(4,6-dimethoxy-2-pyrimidinyl) amino] carbonyl]amino] sulfonyl]methyl]benzoate	H
Bentazon	3-1-methylethyl) - (1*H*)-2,1,3-benzothiadiazin-4-(3*H*)-one 2,2-dioxide	H
Bromoxynil	3,5-dibromo-4-hydroxybenzonitrile	H
Carbaryl	1-naphthyl *N*-methylcarbamate	I
Carbofuran	2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate	I
Fenoxaprop	(±)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid	H
Fentin hydroxide	triphenyltin hydroxide	F
Iprodione	3-(3,5-dichlorophenyl)-*N*-(1-methylethyl)-2,4-dioxo-1-imidazolinecarboxamide	F
Malathion	(*0,0*-dimethyl phosphorodithioate of diethyl mercaptosuccinate)	I
Methyl parathion	*0,0*-dimethyl *0*-(*p*-nitrophenyl) phosphorothioate	I
Molinate	*S*-ethyl hexahydro-1*H*-azepine-1-carbothioate	H
Pendimethalin	*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine	H
Propanil	*N*-(3,4-dichlorophenyl)propanamide	H
Propiconazole	2-[[2(2,4-dichlorophenyl)-4-propyl-1,3-dioxalan-2-yl]methyl]-1-*H*-1,2,4-triazole	F
Thiobencarb	*S*-[(4-chlorophenyl)methyl]diethylcarbamothioate	H
Triclopyr	[(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid	H
2,4-D	(2,4-dichlorophenoxy)acetic acid	H
2,4,5-T	(2,4,5-trichlorophenoxy)acetic acid	H

[1] F = fungicide; H = herbicide; I = insecticide

(*Sida spinosa* L.) in rice fields. Recently, mixtures of *C.g.a.* and *Colletotrichum truncatum* (Schw.) Andrus & Moore have been found to control northern jointvetch and hemp sesbania in rice (R.J. Smith, Jr., 1991, unpublished data).

Formulation can improve mycoherbicide efficacy. Various adjuvants and amendments have improved or modified fungal spore germination, pathogen virulence, or environmental requirements (Boyette *et al.* 1991). Invert (water-in-oil) emulsions have enhanced the activity of mycoherbicides. Recently, *C.g.a.* formulated in an invert emulsion was found to control northern jointvetch and hemp sesbania in rice (Boyette *et al.* 1992). In 1991, *C.g.a.* formulated in an invert emulsion controlled 93 and 100% of northern jointvetch and hemp sesbania, respectively. In contrast, *C.g.a.* spores applied in water suspension controlled only 50% of northern jointvetch, and gave no control of hemp sesbania (R.J. Smith, Jr. 1991, unpublished data).

New strains of *C.g.a.* tolerant to benomyl have been developed by induced mutation (Smith 1991). They appear to be genetically stable and host specific. They also controlled northern jointvetch in rice when benomyl was applied before and after treatment with *C.g.a.* strains.

Integration of Potential Mycoherbicides for Weed Management in Rice

Several pathogens have the potential of controlling important weeds of rice in the United States. Some specific examples follow.

The rust fungus *Puccinia canaliculata* (Schw.) Lagerh. has the potential of controlling yellow nutsedge (*Cyperus esculentus* L.). Release of the pathogen early in the spring on seedling yellow nutsedge reduced plant populations, tuber formation, and flowering (Phatak *et al.* 1987). This mycoherbicide is being developed and commercialized in the United States for control of yellow nutsedge (Phatak 1992). Research is needed to determine the potential of *P. canaliculata* as a mycoherbicide in rice. A valid approach would be to integrate *P. canaliculata* with registered chemical herbicides, including bentazon and bensulfuron methyl.

The endemic fungus *Colletotrichum gloeosporioides* f. sp. *jussiaeae* (*C.g.j.*) controlled winged waterprimrose in rice. *C.g.j.* controlled >80% of weed plants in rice after four weeks (Boyette *et al.* 1979). Because winged waterprimrose is a minor weed of rice in the United states, *C.g.j.* is not an economical alternative for control of this weed.

Colletotrichum truncatum has controlled hemp sesbania in rice (R.J. Smith, Jr. 1991, unpublished data). Hemp sesbania, a severe weed of rice in the southern United States, has been controlled in rice with timely applications of *C. truncatum*. Research is needed to integrate *C. truncatum* into weed and pest control programs in rice.

This fungus *Cochliobolus lunatus* Nelson and Haasis incited leaf necrosis of barnyard grass [*Echinochloa crus-galli* (L.) Beauv.] in the Netherlands and killed one- to two-leaf plants (Smith 1991). Larger barnyard grass plants, 22 and 30 days old, were killed by combined treatments of *C. lunatus* and sublethal rates of atrazine, compared to the moderate leaf necrosis on plants treated with either *C. lunatus* or atrazine. Hence, combined treatments of *C. lunatus* and atrazine are a potential selective control of barnyard grass in corn (*Zea mays* L.). Research is needed to determine if *C. lunatus* is a potential control of barnyard grass in rice. Perhaps combinations of *C. lunatus* with sublethal rates of propanil or thiobencarb would control barnyard grass selectively in rice.

The fungus *Bipolaris setariae* (Saw.) Shoem. controlled broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash] in experiments in North Carolina (Smith 1991). Broadleaf signalgrass, a severe weed of rice, is frequently not controlled effectively by applications of propanil, thiobencarb, or molinate. Research is needed to determine the potential of *B. setariae* for controlling broadleaf signalgrass in rice, and to integrate this fungus into weed control programs for rice.

Integration of Other Biological Controls for Weed Management in Rice

Wild Ducks

Flooding rice fields which are contaminated with red rice during the winter to attract wild ducks reduces red rice grain remaining in the field after harvest. Red rice matures before the rice crop, and the grains shatter easily. Consequently, large quantities of red rice grain may remain on or in the soil of infested fields after the rice crop is harvested. Wild ducks reside in the rice-producing areas of Arkansas during the winter, arriving in late October and leaving in late February. They eat large quantities of rice, including red rice. In an experiment in Arkansas, wild ducks feeding in a rice field contaminated with 420 kg/ha of red rice grain in the fall of 1979 reduced red rice seed by 97% by the spring of 1980 (Smith and Sullivan 1980). Thus, attracting wild ducks to fields infested with red rice by flooding fields in the fall, either by catching rainwater or by pumping in irrigation water, and then keeping the land flooded until late winter, reduces red rice seed and is beneficial in subsequent rice crops. Integrating a wild duck control program with cropping systems (Smith 1989), herbicides (Salzman *et al.* 1988), and cultural and mechanical practices can reduce red rice infestations to below economic thresholds.

Insects

Ducksalad, a severe aquatic weed of rice, was controlled biologically in rice with insects in California. The waterlily *aphid Rhopalosiphum nymphaeae* L. reduced ducksalad biomass by 58-87% and seed pods by more than 82%, without causing any noticeable injury to rice (Oraze and Grigarick 1992). Waterlily aphids also suppressed other aquatic weeds, including California arrowhead (*Sagittaria montevidensis* Cham. and Schlecht.), disc waterhyssop [*Bacopa rotundifolia* (Michx.) Wettst.], and common water plantain (*Alisma triviale* Pursh). Waterlily aphids offer the opportunity of controlling aquatic weeds in rice when they are integrated into control programs against other weeds, insects, and diseases. Because carbaryl and perhaps other insecticides kill waterlily aphids, this control strategy would have to be integrated with insect control programs for rice to prevent damage to the aphid.

Allelopathy

Rice plants produce natural chemicals that can suppress and kill weeds in field environments. They release toxic allelochemicals into the paddy, either as root exudates or from decaying plant materials. These allelochemicals have been known to control ducksalad and other aquatic weeds. Approximately 4% of the 10,000 rice accessions in the United States national small grains collection that have been tested exhibited some allelopathic activity (Dilday *et al.* 1991).

In Arkansas, nine of 38 germplasm lines controlled >80% of ducksalad, purple ammannia (*Ammannia coccinea* Rottb.), and disc waterhyssop (Lin *et al.* 1992). Germplasm with high allelopathic activity produced 6 to 9 times more rice root biomass than Rexmont, a cultivar without allelopathic activity. Rice germplasm with high allelopathic activity differs in origin, grain type, plant height, and maturity. This wide range of variation will be beneficial in using these germplasm lines for developing acceptable rice cultivars with the allelopathic trait.

In one experiment conducted in Arkansas, rice germplasm with high allelopathic activity controlled 72 to 95% of ducksalad, purple ammannia, and disc waterhyssop, compared to 100% control from bensulfuron methyl (Lin *et al.* 1992). Likewise, rice lines with high allelopathic activity, combined with straw of the same lines incorporated into the soil, controlled rice flatsedge (*Cyperus iria* L.) almost as effectively as a tank mixture treatment of propanil and bentazon (Lin *et al.* 1992). This research suggests that rice that possesses high allelopathic activity can control some problem weeds of rice, and may reduce the need for herbicides. Certainly, allelopathy for controlling weeds in rice should be integrated with herbicides as well as cultural and other biological practices. Research is required to develop suitable cultivars with allelopathy, and to integrate biological control strategies with other pest management strategies.

CONCLUSION

Integration of biological control strategies with chemical, cultural, and mechanical control practices is essential to judicious use of biological control in weed and pest management programs in rice production systems. Because biological strategies control a comparatively narrow spectrum of weed species, chemical herbicides are generally required to control the complex of weed species that infest rice. Also, few biological control practices are available compared with the many chemical herbicides available for weed control in rice. Therefore, biological control strategies must be integrated with chemical herbicides for effective management of rice weeds. In addition, diseases and insects that infest rice must be controlled with timely applications of fungicides and insecticides. Consequently, biological control strategies must be integrated with the many chemical fungicides and insecticides used for pest management in rice.

Research and development of registered and experimental microbial herbicides indicate that mycoherbicides can be integrated successfully with chemical pesticides into an effective pest management program. For example, COLLEGO has been integrated successfully with chemical pesticides for control of northern jointvetch with the chemicals giving effective control of other weed species, as well as diseases and insects. Experiments with other biological control strategies also indicate that they are compatible with chemical pesticides for managing pests in profitable rice production, while ensuring a quality environment. Indeed, chemical herbicides combined with microbial herbicides in tank mixtures or timely sequential applications frequently increase the activity of each type of herbicide on target weeds.

As new, improved chemical pesticides are developed for control of weeds, diseases, and insects, continued research will be required to determine the effect they have on microbial herbicides or other biological control strategies, and how they can best be integrated into pest management programs.

Development of new pathogen strains resistant to improved pesticides offers the opportunity of reducing the adverse impact pesticides have on microbial herbicides. Also, research is required to develop genetically altered pathogen strains that have increased pathogenicity on target weeds, and are compatible with the chemical pesticides used in pest management program for rice.

Development of rice cultivars that contain allelochemicals is a new biological control strategy that warrants additional research. Rice germplasm lines have controlled many important weeds of rice. Although the allelopathy strategy appears to be a viable biological weed control approach, it will have to be integrated with chemical herbicides and other biological control practices.

Integration of biological control strategies as viable components of weed management programs will be a challenge to researchers and organizations concerned with pest management sciences. Costs, benefits, and risks of all components of integrated weed and pest management programs must be examined carefully. Biological control strategies offer opportunities for development of improved weed control practices that will be compatible with all components of integrated pest management systems of rice.

REFERENCES

Anonymous. 1989. *Herbicide Handbook*, 6th edititon. Weed Science Society of America, Champaign, IL, U.S.A.

Anonymous. 1990. *Rice Production Handbook*. Misc. Publ. No. 192. University of Arkansas Cooperative Ext. Serv., Little Rock, AR, U.S.A..

Anonymous. 1992a *Recommended Chemicals for Weed and Brush Control*. Misc. Publ. No. 44. University of Arkansas Cooperative Ext. Serv., Little Rock, AR, U.S.A.

Anonymous. 1992b. *Plant Disease Control Handbook*. Misc. Publ. No. 154. University of Arkansas Cooperative Ext. Serv., Little Rock, AR, U.S.A.

Bowers, R.C. 1986. Commercialization of Collego™ — an industrialist's view. *Weed Science* 34 (Suppl. 1): 24-25.

Boyette, C.D., G.E. Templeton and R.J. Smith, Jr. 1979. Control of winged waterprimrose (*Jussiaea decurrens*) and northern jointvetch (*Aeschynomene virginica*) with fungal pathogens. *Weed Science* 27: 497-501.

Boyette, C.D., P.C. Quimby, Jr., W.J. Connick, Jr., D.J. Daigle, and F.E. Fulgham. 1991. Progress in the production, formulation, and application of mycoherbicides. In: *Microbial Control of Weed*, D.O. TeBeest (ed.). Chapman and Hall, New York, U.S.A., pp. 209-222.

Boyette, C.D., R.J. Smith, Jr., H.K. Abbas and J.R. McAlpine. 1992. Bioherbicidal control of hemp sesbania (*Sesbania exaltata*) and northern jointvetch (*Aeschynomene virginica*) in rice with anthracnose pathogen-invert formulations. *Proc. Southern Weed Science Society* 45: 293.

Charudattan, R. 1991. The mycoherbicide approach with plant pathogens. In: *Microbial Control of Weeds*, D.O. TeBeest (ed.). Chapman and Hall, New York, U.S.A. pp. 24-57.

Dilday, R.H., P. Nastasi, J. Lin, and R.J. Smith, Jr. 1991. Allelopathic activity of rice (*Oryza sativa* L.) against ducksalad [*Heteranthera limosa* (Sw.) Willd.]. In: *Proc. Symposium Sustainable Agriculture for the Great Plains*, J.D. Hanson, M.J. Shaffer, D.A. Ball, C.V. Cole (eds.), ARS-89. U.S. Department of Agriculture Agricultural Research Service, Washington, D.C., U.S.A., pp. 193-201.

Hill, G.D. 1982. Herbicide technology for integrated weed management systems. *Weed Science* (Suppl.): 35-39.

Huey, B.A. 1987. How to use the DD50 computer printout. Misc. Publ. No. 211. University Arkansas Cooperative Ext. Serv., Little Rock, AR, U.S.A.

Kendrick, J.B. Jr. 1988. A viewpoint on integrated pest management. *Plant*

Disease 72: 647.

Klerk, R.A. 1983. Use of a microbial herbicide for weed control in rice (*Oryza sativa*). M.Sc. Thesis, University of Arkansas, Fayetteville, AR, U.S.A..

Klerk, R.A., R.J. Smith, Jr. and D.O. TeBeest. 1985. Integration of a microbial herbicide into weed and pest control programs in rice (*Oryza sativa*). *Weed Science* 33: 95-99.

Lin, J., R.J. Smith, Jr. and R.H. Dilday. 1992. Allelopathic activity of rice germplasm on weeds. *Proc. Southern Weed Science Society* 45: 99.

McWhorter, C.G. 1984. Future needs in weed science. *Weed Science* 32: 850-855.

McWhorter, C.G. and W.C. Shaw. 1982. Research needs for integrated weed management systems. *Weed Science* 30 (Suppl.): 40-45.

Oraze, M.J. and A.A. Grigarick. 1992. Biological control of ducksalad (*Heteranthera limosa*) by waterlily aphid (*Rhopalosiphum nymphaeae*) in rice (*Oryza sativa*). *Weed Science* 40: 333-336.

Phatak, S.C. 1992. Development and commercialization of rust (*Puccinia canaliculata*) for biological control of yellow nutsedge (*Cyperus esenlenlus* L.). In: *Proc. First Int. Weed Control Congress* (Vol. 2) Weed Sci. Soc. Victoria, Inc. Melbourne, Australia, pp. 388-390.

Phatak, S.C., M.B. Callaway, and C.S. Vavrina. 1987. Biological control and its integration in weed management systems for purple and yellow nutsedge (*Cyprus rotundus* and *C. esculentus*). *Weed Technology* 1: 84-91.

Salzman, F.P., R.J. Smith, Jr. and R.E. Talbert. 1988. Suppression of red rice (*Oryza sativa*) seed production with fluazifop and quizalofop. *Weed Science* 36: 800-803.

Shaw, W.C. 1982. Integrated weed management systems technology for pest management. *Weed Science* 30 (Suppl.): 2-12.

Shaw, W.C. 1984. The new weed science: A view of the 21st century. *Proc. Western Weed Science Society* 37: 8-29.

Smith, R.J. Jr. 1982. Integration of microbial herbicides with existing pest management programs. In: *Biological Control of Weeds with Plant Pathogens*, R. Charudattan and H.L. Walker (eds.). Wiley, New York, U.S.A. pp. 189-203.

Smith, R.J. Jr. 1986. Biological control of northern jointvetch (*Aeschynomene virginica*) in rice (*Oryza sativa*) and soybeans (*Glycine max*) — A researcher's view. *Weed Science* 34 (Suppl. 1): 17-23.

Smith, R.J. Jr. 1989. Cropping and herbicide systems for red rice (*Oryza sativa*) control. *Weed Technology* 3: 414-419.

Smith, R.J. Jr. 1991. Integration of biological control agents with chemical pesticides. In: *Microbial Control of Weeds*, D.O. TeBeest (ed.). Chapman and Hall, New York, U.S.A., pp. 189-208.

Smith, R.J. Jr. and J.D. Sullivan. 1980. Reduction of red rice grain in rice fields by winter feeding of ducks. *Arkansas Farm Research* 29,4: 3.

Templeton, G.E. 1992. Potential for developing and marketing mycoherbicides. In: *Proc. First Int. Weed Control Cong.* (Vol. 1), J.H. Combellack, K.J. Levick, J. Parsons and R.G. Richardson (eds.). Weed Sci. Soc. Victoria, Inc. Melbourne, Australia, pp. 264-268.

Toenniessen, G.H. 1990. Rice biotechnology: progress and prospects. In: *Pest Management in Rice*, B.T. Grayson, M.B. Green, and L.G. Copping (eds.). Elsevier Sci. Publ. Co. Inc., New York, U.S.A. pp. 514-536.

Watson, A.K. 1992. Biological and other alternative control measures. In: *Proc. First Int. Weed Control Cong.* (Vol. 1), J.H. Combellack, K.J. Levick, J. Parsons and R.G. Richardson (eds.). Weed Sci. Soc. Victoria, Inc. Melbourne, Australia. pp. 64-73.

DISCUSSION

Dr. Moody was interested in the possibility that weeds might develop resistance to bioherbicides. Dr. Smith replied that many weeds in USA are now showing herbicide resistance, and there is always a possibility of secondary resistance to Collego. In some fields it had been found difficult to control weeds with Collego, and he suspected that some of the plants in these fields were more tolerant of Collego than those elsewhere. However, since Collego has not been used for very long, Dr. Smith felt that this did not represent the build-up of resistance, but the fact that some plants in the weed population are less susceptible to it. He felt that over a period of some years, it would be quite possible for resistance to develop.

Dr. Fujii was interested in allelopathy in rice, and in Dr. Smith's data that rice lines with allelopathy produced a root biomass 6-9 times greater than those without allelopathy. He referred to data from a previous paper presented at the same seminar* which showed that weed resistant rice cultivars in Southeast Asia also have a very large biomass, particularly above ground. He asked whether there might be other relevant factors, such as physical factors or competition for nutrients, which are not related to allelopathy. Dr. Smith felt it was likely that allelopathic varieties would have a higher root mass, since there would be more biomass to produce more allelochemicals. He pointed out that many rice types with a large root biomass are also more tolerant to drought stress. However, he felt that there was little difference between short statured or tall rice types with regard to their allelopathic effect: some short types are strongly allelopathic and others are not, while the same is true of tall rice types.

* See Vongsaroj this volume (pp. 32-45).