Chapter VII

Azolla, A Low Cost Aquatic Green Manure for Agricultural Crops

Thomas A. Lumpkin
Department of Agronomy and Soil Science
College of Tropical Agriculture
University of Hawaii
Honolulu, Hawaii
and
Donald L. Plueknett
Consultative Group on international
Agricultural Research
World Bank
Washington, D.C.

Contents

Figures

Chapter VII

Azolla, A Low Cost Aquatic Green Manure for Agricultural Crops

INTRODUCTION

The air we breathe is 79 percent nitrogen. Plants need nitrogen to make the proteins that allow them to harvest sunlight and carry on natural processes. Unfortunately, nitrogen in the air is in an inert N_2 form that cannot be used by plants. Only two kinds of organisms have the ability to convert inert atmospheric nitrogen to a usable form such as ammonia, These two organisms are blue-green alga (cyanobacteria) and certain species of bacteria. Rhizobium bacteria are the nitrogen-fixing partners of the well-known legume/Rhizobium symbiosis of soybeans, alfalfa, etc. The blue-green alga *anabaena* are the nitrogen-fixing partners of the virtually unknown *Azolla/Anabaena* symbiosis,

Until this century, nitrogen-fixing bacteria and blue-green alga, existing under freeliving or symbiotic conditions, produced most of the new nitrogen entering the cropping system. Almost all farmers had to include legumes in their crop rotation in order to maintain soil fertility. This traditional practice continued until the discovery of fossil-fuel-dependent methods of producing nitrogen fertilizer that radically changed the economics of agriculture, The use of legumes in crop rotation was soon considered to be too expensive and troublesome and fell into disuse, except when grown as a cash crop. The change was most apparent in developed countries and in developing countries that adopted the “green-revolution” technology.

However, during the *1970s* this change began to reverse itself, The rapidly rising price of fossil fuel-dependent nitrogen fertilizers caused the economics of agriculture to shift again, Rising prices are causing researchers to seek alternative methods for producing synthetic fertilizer and causing farmers to reconsider traditional methods for maintaining soil fertility.

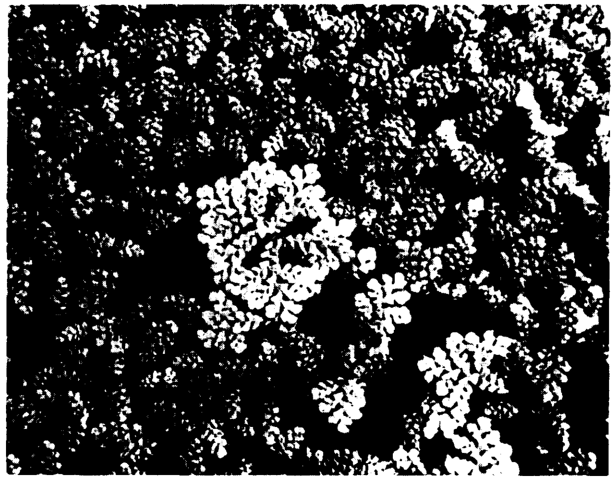
The traditional legume crops are and will continue to be the most commonly used nitrogen-fixing green manures, especially for upland crops. However, they have certain weaknesses for rice farmers. One of these weaknesses is that rice is traditionally grown on the most fertile and, consequently, intensively managed land. Rice farmers are reluctant to use part of the valuable growing season on a relatively slow-growing, legume green manure crop, Another problem is that many rice paddies are flooded or waterlogged, particularly during the potentially productive early part of the rice season when most of the transplanted rice is still in the nursery beds. Unfortunately, under waterlogged or flooded conditions most legumes cannot grow or fix nitrogen, so usually the paddy fields stand idle for a month or more while the rice seedlings mature in the nursery beds. The fast-growing aquatic Azolla has neither of these two weaknesses,

What Is Azolla?

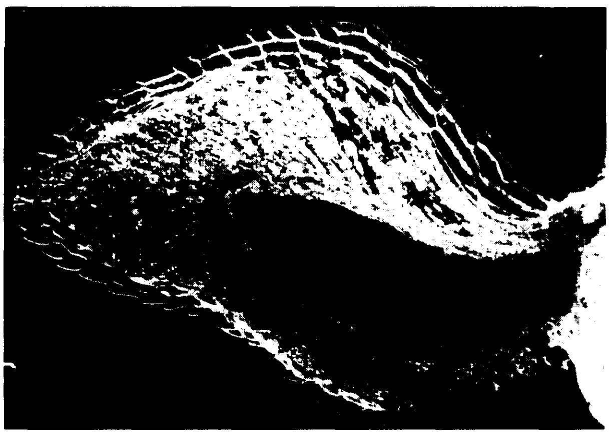
Azolla is a genus of small aquatic ferns that are native to Asia, Africa, and the Americas (figure 1), Three *Azolla* species are native to parts of the United States, They live naturally in lakes, swamps, streams, and other bodies of water, Some have been spread by man or natural means to various parts of the world. Some are strictly tropical or subtropical in nature, while others grow and thrive in either temperate or tropical climates. Azolla has been of interest to botanists and agriculturists for years because of its symbiotic relationship with a nitrogen-fixing, blue-green alga, *Anabaena*.

Figure 1.—Azolla

W az



M



az

az

Cells of the nitrogen-fixing blue-green algae, *Anabaena,* look like a string of beads. The larger egg-shaped cells specialize in producing nitrogren fertilizer while the more numerous smaller cells harvest sunlight.

R n h m nd n g n manu fl d d p p n d d n Ch n nd Vietnam.

The Azolla/Anabaena Relationship

The most remarkable feature of azolla is its symbiotic relationship with the blue-green alga, *Anabaena azollae.* The delicate fern provides nutrients and a protective leaf cavity for the *Anabaena,* which in turn provides nitrogen for the fern. Under suitable field conditions, the fern/alga combination can double in weight every 3 to 5 days and fix atmospheric nitrogen at a rate exceeding that of the legume/*Rhizobium* symbiotic relationship. Azolla can accumulate up to 2 to 4 kilograms of nitrogen/

ha/day (equivalent to 10 to 20 kg of ammonium sulfate), and since the *Azolla/Anabaena* combination grows in aquatic conditions, it can provide a potential nitrogen source for flooded crops such as rice. The exploitation of this potential is a challenge to agricultural scientists.

What Are the Benefits of Using Azolla?

Producing Nitrogen Fertilizer for increasing Crop Yields

Azolla plants are described by the Chinese and Vietnamese as being miniature nitrogen fertilizer factories. Indeed the Vietnamese call them indestructible fertilizer factories, since azolla continued to produce nitrogen fertilizer for Vietnamese rice paddies even during the height of the Vietnam war.

The nitrogen fertilizer fixed by azolla becomes available to the rice after the azolla mat is incorporated into the soil and its nitrogen begins to be released through decomposition. In 25 to 35 days azolla can easily fix enough nitrogen for a 4 to 6 ton/ha rice crop during the rainy season, or a 5 to 8 ton/ha crop under irrigation during the dry season.

Maintaining Soil Fertility

As a green manure, azolla's influence on soil fertility is due to its organic matter and nitrogen. A humus compound is formed as a result of the incorporation and decomposition of azolla. Humus increases the water holding capacity of soil and promotes aeration, drainage, and the aggregation essential for highly productive soils, Organic matter can bind together soil particles and makes clayey soils more friable.

In addition to its influence on soil physical properties, azolla is important in the cycling of nutrients, While azolla is growing in the paddy, it fixes nitrogen and also absorbs nutrients out of the water that might otherwise be washed away. When the azolla is incorporated into the soil and humus is formed, these nutrients are slowly released into the soil as decomposition progresses.

Even though azolla appears to be a rather delicate plant that would rapidly decompose, it actually takes six weeks or more for most of the nutrients to be released because the plant has a rather high lignin content. Slow decomposition gives a natural slow release effect that is ideal for efficient absorption of the nutrients released. Another factor in azolla effectiveness as a green manure is its low carbon to nitrogen ratio of about 10:1. This high ratio ensures that azolla nitrogen will not be tied up by bacteria that are involved in decomposition of an over abundance of carbonaceous plant residues.

Producing Fodder for Pigs, Ducks, and Fish

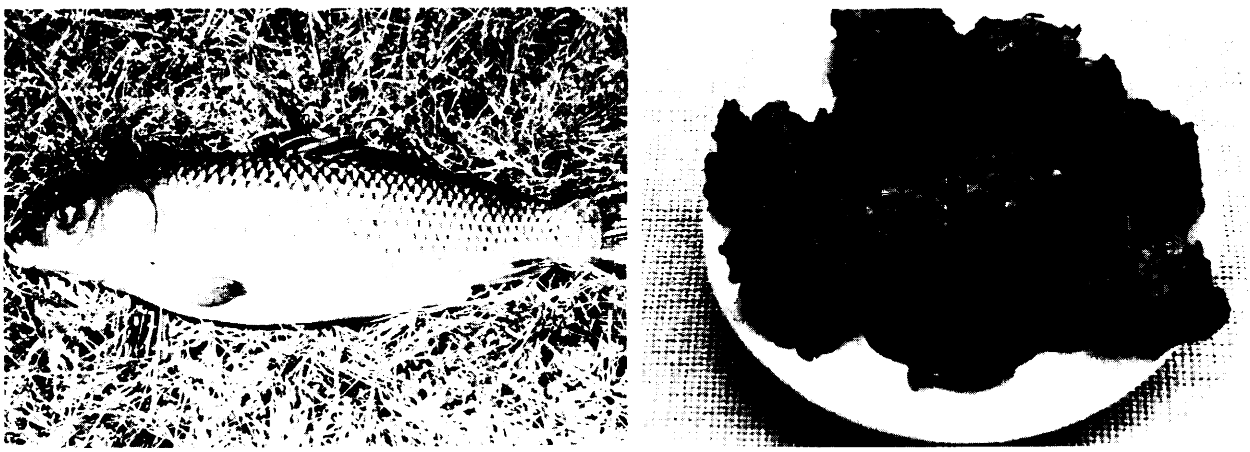
Azolla has traditionally been used as a fodder throughout Asia and parts of Africa. It is fed to pigs, ducks, and fish (figure 2), The grass carp *(Ctenopharyngodon idella)*, Israeli Carp *(Cyrinus carpis)*, and *Tilapia mossambica* prefer azolla over most other aquatic weeds as a source of food, Small lots of azolla growing in canals and ponds as food for pigs and ducks are ubiquitous throughout southern China. Azolla as a fodder probably has a longer history than as a green manure, There may even be potential for direct consumption by man, In India, women make a tasty deep fried dish of azolla mixed with batter (7),

On a dry weight basis, azolla has a protein content between 13 to 24 percent, One hectare of azolla can produce 1 to 2 tons of fodder per hectare per day, equivalent to 10 to 30 kg of protein per day. When these statistics are considered, azolla has a tremendous potential as a fodder crop in developing countries and also in the United States.

Recent work in India at G. B. Pant University indicates that azolla maybe useful as a fodder for cattle. In trials there, growing heifers gained 0.33 kg/day when fed 0.9 kg of dried azolla with 2.1 kg of a 2:1 ratio of dry wheat straw and sugarcane tops. Control animals that were fed the same amount of wheat straw and sugarcane tops, but also received 1.5 kg of a concentrate feed, gained only 0.14 kg/day (l).

Figure 2.—Azolla as Food and Fodder

Although azolla is most commonly used as an organic fertilizer for rice, it can also be used as a fodder for pigs (left), duck (center) and fish and as a compost (right) for upland crops. Many of the pigs which are grown to produce China's famous Jin-hua hams are fed on a diet which includes azolla.



Azolla is a preferred forage for many species of herbivorous fish. Azolla may also have potential for direct consumption by man if attractive uses can be developed. The photo on the right shows a deep fried dish of azolla mixed with batter.

Suppressing the Growth of Aquatic Weeds

Agricultural economists have estimated that Asian farmers, particularly women, spend more time weeding than on any other activity required for rice production. Although research is insufficient, it is commonly believed that azolla suppresses the growth of certain aquatic weeds. Weed growth is suppressed when azolla forms a thick, virtually light-proof mat. There are probably two mechanisms for this suppression, the most effective being the light-starvation of young weed seedlings by the blockage of sunlight. The other is the physical resistance to weed seedling emergence created by a heavy, interlocking azolla mat. In some weed-infested rice fields, the benefit from azolla weed suppression may even surpass its benefit as a nitrogen source. Rice seedlings are not affected by azolla's weed suppression effect because, when transplanted, they stand above the azolla mat.

THE PRESENT STATUS OF AZOLLA

Where Azolla Is Being Used in Agriculture

Azolla is already being grown commercially in China and Vietnam, where its usefulness has been known for years, Once restricted in use because of propagation problems, the fern is now being used in larger crop areas (figure 3),

Chinese use of azolla goes back hundreds of years, at least to the Ming dynasty, Its use in Vietnam dates to the 1lth century. These two are the only countries with a long history of azolla cultivation. The practice probably began with recognition that the spontaneous growth of wild azolla in rice fields had a beneficial effect on the crop. Organized use of the fern could not occur, however, until reliable methods were developed to overwinter and oversummer the fern. Since azolla can only be grown from vegetative material, it must be protected during seasons that are too severe for its survival.

The original sites of azolla cultivation are thought to have been Zhejiang Province in China and Thai Binh Province in Vietnam. Until recently certain villages in these places had temples dedicated to the mythological discoverers of azolla. At the end of the 19th century azolla was being cultivated at favorable sites along the east Asian Coast as far south as 200 N latitude on the Red River delta in Vietnam and northeastward through Guangdong and Fujian Provinces to Wenzhou District near 280 N latitude in Zhejiang Province, China.

A major push for expanding the use of azolla began in China and Vietnam in the early 1960s. Before that time it was common for certain families or villages that had mastered the intricate techniques of oversummering and over-

Figure 3.—Geographic Distribution of Azolla

Distribution of *Azolla* species throughout the world, This distribution map is rapidly becoming outdated because many azolla species and varieties are being moved about and introduced into new places as research on azolla grows.

wintering azolla to control the supply of azolla-starter-stocks in the spring. Peasants had to travel to these villages to purchase their spring plants.

After the revolutions in China and Vietnam, the new governments eventually recognized the worth of azolla and began officially promoting its use and organizing the construction of propagation centers.

During colonial days in Vietnam, French scientists reported on the use of azolla and did some preliminary research, but its cultivation was never promoted officially. At the end of the colonial period, azolla was grown on about 40,000 hectares[1] as a green manure during the winter for the spring rice crop. In 1958, the new government established an azolla research center at the Crop Production Research Institute and set up an extension network with over 1,000 inoculum production bases to stimulate use.

Despite this promising beginning, the big push in azolla research did not come until the early 1960s. Articles on azolla began appearing in 1962, culminating in several articles and a large book (9).

Since the introduction of high yielding rice varieties to Vietnam in the early 1960s, most azolla has been grown as a monocrop before the spring rice. The cultivated area reportedly doubled from 1965 to about 700,000 hectares in 1978. As in China, azolla cultivation in Vietnam is seldom practiced in summer because the *A. pinnata* var. *imbricata* native to the Asian continent is sensitive to high temperatures and insects.

Vietnamese scientists have collected over 30 varieties of local azolla and have selected superior strains for heat, cold, salt, and acid tolerances. Despite these advances, reportedly most communes and cooperatives have not adopted these improved azolla varieties.

The Chinese story is much the same as that of Vietnam, although much more was known of the Vietnamese experience because of the availability of publications in English and French as well as in Vietnamese. Recently, information from China has become available (3,4,11,2,5).

Today, azolla is grown as a green manure on about 1.3 million hectares of rice in China. Research and development activities have increased significantly, as have extension activities to promote its use. Large posters have been produced to inform the public of azolla's usefulness and of its management requirements.

How Azolla Is Used as a Green Manure

Azolla can be used as a green manure (figure **4**):

- by growing it as a monocrop and then incorporating it as a basal manure before the rice is transplanted; or transported to another site for use on upland crops;
- growing it as an intercrop and incorporating it as a top dressing manure after the rice is transplanted; or
- by growing it both as a monocrop and an intercrop.

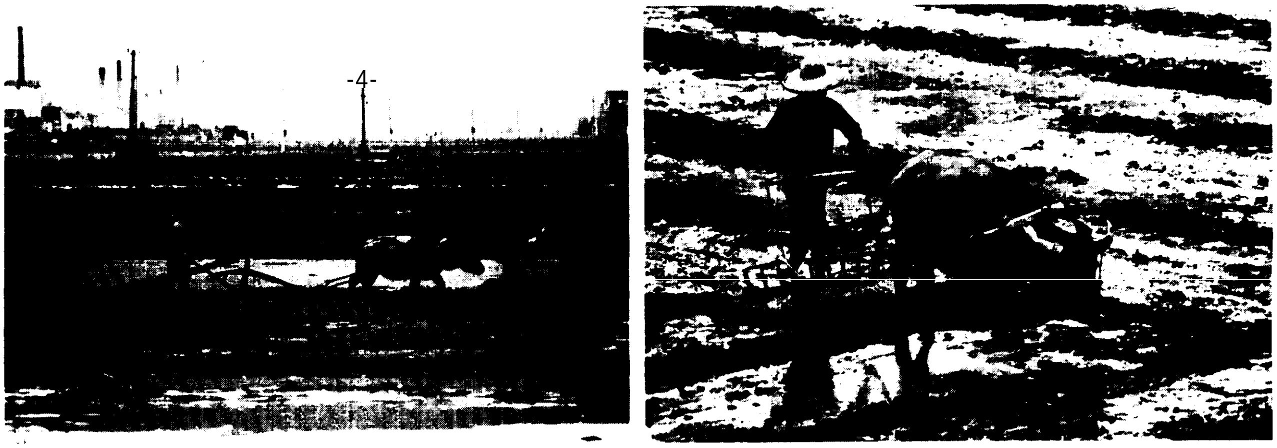
All three systems can be successful but, as is common in agriculture, use of the green manure crop requires some adjustments in management of both the green manure and the main crop.

Monocrop Azolla is used in China and Vietnam during winter and spring to produce nitrogen for the spring rice crop. The same technique is used to produce nitrogen for the early summer rice crop, but this is less common since the growth of *Azolla pinnata* is affected by high temperature and heavy pest attack during mid to late summer.

Intercropped Azolla is usually grown with the rice in places where there is no time available in the cropping system for the monocropping of azolla. As an intercrop azolla will be initially incorporated by hand or rotary rice weeder and then later killed by heavy shading and/or high temperatures—with subsequent decomposition and release of nitrogen to the crop—at the stage of maximum rice tillering.

[1] 1 hectare = 2.47 acres.

Figure 4.—Incorporating Azolla Into Soil



Two of several methods for soils incorporating a monocrop of azolla as a basal green manure for rice. Both photos were taken during the spring of 1980 in Guangdong province, China. The photo on the left is *A. filiculoides,* the photo on the right is *Azolla imbricata*

图36 用萍推赶萍

图37 用竹竿赶萍

The photo on the left shows an azolla beater being used to spread inoculum azolla after it was introduced into the field of a second later summer rice crop to grow with the-rice as an intercrop.

The top center photo shows an azolla pusher which is used to spread inoculum azolla if it is applied to a rice crop after the rice is transplanted, or is used to concentrate and collect azolla in a nursery. The bottom center photo shows a bamboo pole being used to collect azolla growing in a canal.

Growing both monocrop and intercropped Azolla is a technique that is designed to use the growing period for azolla before the planting of the rice crop, *plus* production of added nitrogen for the crop through cultivation of intercropped azolla, In this system two different varieties of azolla may be used in each of the different periods. Different temperature and light sensitivities of azolla varieties make this possible.

Who Is Doing Azolla Research?

A number of centers are conducting azolla research. Most of this work is less than 5 years old. Both China and Vietnam are studying *Azolla pinnata* var. *imbricata* under their own conditions. Recently, the Zhejiang Academy of Agricultural Sciences has had an opportunity to evaluate the other *Azolla* species *(carolinian, filiculoides, mexicana, microphyhlla,* and *nilotica)* for use in China.

Many developing country rice research centers have begun azolla research, but with little success to date. Probably the most successful program is in Thailand, where the Ministry of Agriculture has been sponsoring an azolla program that has progressed through the regional extension stations and has now reached the stage of demonstration plots in the fields of progressive farmers.

The International Rice Research Institute started an azolla research program nearly 8 years ago (10), IRRI is studying the use of several azolla species for use in flooded rice.

There are three major centers of azolla research in the United States. One is the University of Hawaii, where agronomic and physiology studies are underway to characterize and understand the usefulness of all azolla species in tropical crop production systems, including rice and taro (5). The work is led by T. A. Lumpkin who was selected by the National Academy of Sciences to conduct research on azolla in the People's Republic of China in 1979 and 1980 at its foremost azolla research center, the Zhejiang Academy of Agricultural Sciences at Hangzhou.

Studying azolla management to fit temperate, broadcast-sown production systems is the focus of the research program at the University of California at Davis (8). Research objectives at UCD include use of *A. filiculoides* as a monocrop basal green manure crop for springsown rice and *A. mexicana* as an intercrop in rice. The UCD program received a grant from the USDA Competitive Grants Program in 1980 and a grant from the National Science Foundation.

Basic physiology studies are the focus of the program at the Kettering Laboratory focused on understanding the *Azolla/Anabaena* relationship (6). The program has been supported by a grant from the National Science Foundation and a grant in 1979 from the USDA Competitive Grants Program.

Another azolla research program that we know less about is at Virginia Commonwealth University, where the isolation and reconstitution of the *Azolla/Anabaena* association are being studied. This work has been supported by a grant from the USDA Competitive Grants Program; the first grant was made in 1979. Dr. Jack Newton of the USDA in Peoria, Illinois, has done some research on isolation of *Anabaena* from *Azolla.*

Countries that have initiated or plan to initiate azolla research include: India, Nepal, Thailand, Bangladesh, Burma, Indonesia, Malaysia, The Philippines, Sri Lanka, Egypt, Peru, and the West African Rice Development Association, headquartered in Liberia. In addition, several other countries have expressed an interest in the fern and its uses.

What Organizations Are Financing Azolla Research?

Current financial support for azolla research in the U.S. comes from AID (a small 211(d) grant), the National Science Foundation (2 grants), and the USDA (Section 406 and Competitive Grants). The USDA Competitive Grants office has made three grants totaling $278,000 to the University of California at Davis, Kettering Laboratory, and Virginia Commonwealth University. The National Science Foundation has made two grants: one each to University of California at Davis and Kettering Laboratory. In all probability, less than $300,000 per year is now being invested in azolla research in the United States, The work at Hawaii is sponsored by small 211(d) grant for nitrogen fixation from the Agency for International Development and by a research grant from the U. S.D.A. under the Section 406 program of the 1966 Food for Peace Act, and by Hawaii Agricultural Experiment Station funds,

AZOLLA'S EFFECT ON THE NEED FOR AGRICULTURAL INPUTS

Fertilizers

Successful cultivation of azolla requires the application of a certain amount of phosphorus fertilizer (0.5 to 1.0 kg p/ha/week), but this does not necessarily mean an increase in the amount of phosphorus fertilizer required to produce a crop of rice. The application of phosphorus is usually necessary for a good crop of rice, but instead of applying it directly to the rice, the phosphorus can be given to the azolla first in small weekly applications. Once the azolla is incorporated into the soil and begins to decompose, the phosphorus becomes available for the rice crop. Thus phosphorus originally intended for the rice crop is first cycled through the azolla. The phosphorus enables the azolla to grow and fix nitrogen that will be used by the rice. One kilogram of phosphorus applied to azolla results in the fixation of 5 kilograms of nitrogen, North Vietnam is deficient in petroleum products for the production of nitrogen fertilizer, but has sufficient phosphate deposits to fuel its miniature azolla nitrogen factories.

In certain deficient soils, azolla responds to the applications of other nutrients such as potassium, but these usually must also be applied for a high yielding rice crop. In some rare deficient soils, the addition of small amounts of molybdenum and/or iron have proved useful to increase azolla's rate of nitrogen fixation. The Chinese often apply river mud, ash, and animal manure to supplement the phosphorus given to azolla.

Pesticides

Azolla is attacked by larvae of several species of moths and midges and by certain kinds of snails and beetles. These pests are especially destructive during the summer season and must be carefully controlled or the azolla can be devastated. However, azolla is usually not cultivated on a large scale during the seasons when insects are rampant, but is maintained in oversummering nurseries, In addition, even when azolla is cultivated in the field during the summer season, the pesticides normally used on rice crops, such as diptenex, sumithion, malathion, and carbofuran are usually adequate for controlling azolla insects,

Irrigation

Azolla is a delicate, freefloating aquatic plant. Although it can last for months in a refrigerator, it cannot survive for more than a few hours on a dry soil surface under direct summer sunlight, Since technology has not been developed for the use of azolla seeds (spores) in cultivation, a small amount (1 to 10 percent of inoculation requirements) of azolla plants must be maintained through the seasons when azolla is not being cultivated in the fields. This means that in tropical and subtropical areas a certain amount of water must be available throughout the year either to maintain azolla in nurseries or to cultivate it in the fields. The oversummering maintenance of azolla should not be a problem in regions where standing water is present throughout the year, such as in Bangladesh, or in regions where azolla can be maintained in small nurseries beside mountain springs.

The period when irrigation is most critical is when azolla is to be grown in the fields as a green manure. If azolla is cultivated as a monocrop before the rice, which is the most effective way, water must be available for flooding the fields. If water is not available, azolla cultivation will have to be delayed until it can be grown as an intercrop with the rice. Azolla grows as an intercrop with rice during the first **20** to **30** days after transplanting. In this period, the paddy fields must remain flooded with at least a few centimeters of water, Although some species of azolla can survive on mud, as is commonly seen in Hawaiian taro fields, they need standing water for good growth. Thus rice paddies dependent upon rain water, where short periods of drought often occur during the first month of rice cultivation, will not be suitable for azolla cultivation. Also, if extremely hot periods occur when water temperatures exceed 40°C, cooler water must be available for pumping into the fields to prevent the azolla from dying of heat stress.

Even though azolla cultivation require some extra irrigation water, it must be remembered that in fields where little or no nitrogen fertilizer is used, the cultivation of azolla will significantly increase the efficiency of water use. If azolla increases the yield of rice from 2.5 tons to 5 tons, then the efficiency of water use has nearly doubled.

Machinery

The need for machinery is not a handicap to successful azolla cultivation. Even the most primitive villages can manufacture the basic tools required for the cultivation of azolla. These are made from such locally available raw materials as bamboo and wood. A simple metal/wood tool, costing a few dollars, for incorporating intercropped azolla into the soil can be manufactured in villages by a blacksmith. This tooI is not essential, but is more efficient than soil incorporation by hand. An even more efficient multiple row incorporating machine, with a small gas engine, would have to be manufactured commercially.

THE POTENTIAL USE OF AZOLLA

How Does Azolla Affect the Productivity of Tropical Soils?

Azolla affects soils in the same way as any other nitrogen-fixing green manure. It contributes nitrogen, which, after water, is the most common limiting factor to higher crop yields. The application of nitrogen to increase crop yields is the cornerstone of the “green revolution.” All new rice varieties are bred for high yielding response to nitrogen fertilizers.

The loss of organic matter is a primary cause of decreasing crop yields in the Tropics. A decrease in soil organic matter results in soil structure deterioration, lower plant nutrient reserves from the organic matter, and a lower cation exchange capacity. Cultivated tropical soil tend to have lower organic matter contents and soil nitrogen than undisturbed tropical soils. This is especially true with Oxisols and Ultisols.

The Potential Use of Azolla

What is the likelihood of Azolla widespread use? Azolla is cultivated as a green manure on about 2 percent of the harvested rice area of China and about 5 percent of the spring rice crop. In Vietnam, azolla is grown as a winter green manure for 8 to 12 percent of the country’s total harvested rice area, and about **40** to **60** percent of the irrigated spring rice in the

Red River delta. Estimates of China's terrestrial green manure crop (mostly legumes) are as high as 7 million hectares, or about five times the total estimated cultivation area of azolla.

As strains or species of azolla are found that are less sensitive to high water temperatures during summer, the areas of azolla in China and Vietnam will probably expand.

The major areas where azolla should prove useful in rice production in the Tropics are those where: 1) rice is transplanted, 2) labor is plentiful, and 3) some control of irrigation water is possible. Also, countries with effective research and extension services may have more success with popularization of azolla.

Azolla technology is not applicable yet for areas where rice is broadcast-sown, except as a monocrop, preplant, basal green manure. An azolla mat can suppress tiny, broadcast-sown rice seedlings; for that reason, intercropped azolla will probably not be successful in broadcast-sown rice unless it is inoculated in the fields after the rice seedlings have become established and are growing well above the water surface.

With the above criteria in mind, the most likely countries to adopt azolla include parts of India, Bangladesh, Thailand, Indonesia, Philippines, Nepal, Peru, and the Dominican Republic.

A RESEARCH, DEVELOPMENT, AND IMPLEMENTATION PROGRAM

The Program Elements

Two basic azolla management systems need research attention; these are: *1)* tropical, labor intensive systems; and 2) temperate, capital intensive systems, The tropical systems will be focused mainly on developing countries, and will include these principles:

- labor intensive,
- land intensive,
- small farm based,
- crop intensive,
- maximizing opportunities for year-round production,
- first priority to more intensive use of azolla in transplanted rice systems, and
- second priority to use in broadcast-sown systems.

The tropical program should set the following objectives:

1. To find azolla varieties that are less sensitive to high water temperatures (above 27° C) and pest and disease attack. This would have the effect of expanding azolla use from its present primary role as a spring green manure and its secondary role as a fall green manure to the point where it could be a primary green manure in summer in transplanted rice.
2. To collect and characterize all of the six known azolla species, and to evaluate them for use year-round in tropical transplanted rice production systems. [Note: in 1980 preliminary studies by Lumpkin and his Chinese co-workers in China, *A. microphylla* shows great promise as a summer green manure in south Central China, and a winter green manure in the south. Also, *A. nilotica* shows promise as a fall green manure in China. Neither of these species has ever been tested in rice before. Further mission-oriented research could have high payoff in the near future.]
3. After characterization and early testing, distribute promising strains to national program centers for synthesis, design, and testing of new rice cropping systems based on azolla as a green manure.

Temperate, capital-intensive rice production systems, primarily centered on broadcast-sown or drill-sown rice. This work should focus on developed countries, and on middle-income countries (e.g., Brazil and Colombia, and other countries, primarily in Latin America where similar rice production systems are used).

What Organizations Should Be Involved?

In the United States there are two places where azolla is being studied for use in agriculture. The University of California at Davis is conducting research on azolla for use in temperate zone, broadcast-sown rice, and would be the logical leader for the temperate rice work, The University of Hawaii has a program on evaluation of azolla for use in tropical production systems, and would be the logical leader for the tropical efforts. Kettering Laboratory, Virginia Commonwealth University and USDA have specialized programs that could play supporting basic research roles for the temperate and tropical programs.

Links to developing countries will be necessary. Important programs elsewhere include the Zhejiang Academy of Agricultural Sciences, Hangzhou People's Republic of China, (the University of Hawaii has a cooperative program there already); the Fujian Province, PRC (IRRI has links with this group); IRRI, and national programs in Thailand, India, and Nepal. Several national research programs were initiated after an FAO-sponsored azolla training mission by T. A. Lumpkin in 1977. Also T. A. Lumpkin and J. L. Walker of the University of Hawaii, on behalf of the Inter-American Development Bank, visited Uruguay, Brazil, Peru, and Colombia in 1979 to assess the potential for azolla in those countries.

The West African Rice Research and Development Association (WARDA) is also interested in establishing an azolla research program, and they should be tied into the tropical network,

What Is the Necessary Level of Financial Support?

We will speak first of priority areas of research. There is need to carry out several priority activities soon. These include:

- More extensive and complete collection of azolla species and varieties for evaluation in agriculture. Indeed, collection should *take precedence over efforts to breed azolla* because the array of variability available in nature is clearly great, and this should be collected and characterized before beginning breeding programs.
- Characterization of azolla varieties as to tolerance of high and low temperature, phosphorus levels in water, pH, light, and other growing conditions should be of high priority.
- Testing and fitting existing azolla varieties into rice production systems should receive high priority.

These three priority areas should receive first attention for funding. Related basic research on physiology of the *Azolla/Anabaena* symbiosis, biochemistry of the association, etc., can probably be funded through basic research grants from NSF or USDA.

The applied aspects of collection, characterization for use in agriculture, and fitting into rice production systems could be done for the Tropics for about $400,000 to $600,000 per year. This would allow funds for collaborative collecting trips to assemble a wider germplasm base, to conduct screening trials for tolerance to the physical and growing environment, and to run first assessments of potential usefulness in production systems. Such funding would also allow some limited funds for working with collaborators in a tropical azolla network, It would be desirable to have some funds for assisting, through small subgrants, the conduct of specific desired research programs in cooperating countries.

Training, both nondegree and degree, should receive attention early in the program. The first training should emphasize azolla research techniques (e.g., many programs have failed because researchers did not know how to keep azolla alive during hot or cold weather). Later, training could begin to stress field management, We believe the general principle to follow in funding azolla research is probably that continuity of funding over the first several years will be more effective than heavy funding over a shorter time. Collecting, characterizing, and evaluating production systems needs to be done by a team that will require continuity for effectiveness. Such a team should inelude an algologist or cyanobacteria specialist. It should have access to laboratory, greenhouse, and field facilities. The tropical leading institution should be able to grow azolla in the field at any time of the year, and to grow azolla in such a way that all growth stages can be available at any time.

The temperate program will probably require funding in the same order of magnitude as the tropical program. The temperate network may be easier to establish because: 1) the potential countries involved are either in the developed or middle income categories and therefore may have more resources at their disposal, and 2) the countries' institutional research capacity will be much stronger than those of the tropical LDCs.

Some savings may be made and efficiency gained through close cooperation between the temperate and tropical programs. Joint collection trips and close adherence to jointly—determined protocols for testing and evaluation within the networks should save both time and funds.

What Are the Personnel Requirements?

We believe the major research networks should be oriented toward practical adaptation of azolla to agricultural production. Therefore, agronomists with strong physiology and field production backgrounds will be required, As was previously stated, specialists in blue-green alga should be available in the parent institution or nearby.

The program should provide for laboratory and greenhouse assistance, as well as field workers for the field experiments, It is probable that some of this work may be provided by graduate students and student help and by existing institutional farm staff, but some full-time assistance will be needed.

Research assistantships should be provided in the program; this will get the training program going as early as possible.

What Are the Attitudes of Those Who Would Be Affected?

Most research organizations have become aware of azolla and have some idea as to its potential. A few extension specialists (notably in rice) probably also know something about it. Beyond that, except in China and Vietnam and a few individuals in developed countries, the farmers would know nothing of the plant and its potential use in rice. It may be that since azolla is already used successfully in China and Vietnam it may be easier to popularize elsewhere.

What Are Conducive Conditions for Implementation of the Technology?

Conditions conducive to azolla use in the Tropics include:

- transplanted rice;
- rural labor supply;
- assured water supply and some control of water; and
- also, for now, places that grow spring or late summer/fall rice crops because of the high temperature susceptibility of *A. pinnata* in summer.

For rice in temperate zones, the conducive conditions are much less certain because success has not yet been conclusively demonstrated. Factors thought to be important for broadcast-sown rice include:

- growing cold-tolerant azolla (e.g., *A. filiculoides)* as a monocrop green manure to be incorporated into the soil before sowing;
- growing heat-tolerant, shade-sensitive azolla as an intercrop with the broadcast sown rice during the summer; and
- having an assured source of water to grow the monocrop azolla before planting of rice.

Where Do Conducive Conditions Exist and Where Are They Likely to Develop?

Most of the countries of Asia have conducive conditions for use of azolla. Special opportunities for success seem to be present in Thailand, Bangladesh (aus crop), and the Philippines (irrigated dry season crop). In Latin America, Peru and the Dominican Republic appear to have the proper rice production systems to make Azolla use a possibility.

What Is the Sequence of Steps Leading to Successful Implementation?

The first two things a country must learn to do are how: 1) **to** keep azolla plant materials alive year-round and 2) to multiply azolla stocks in order to have inoculant materials available for use in the rice crop. Principles for such techniques can be learned in training programs at the network headquarters or azolla research centers. Such techniques need to be taught widely to extension workers and to innovative farmers.

In some conditions in Asia, *A. pinnata, A. pinnata* var. *imbricata* and perhaps *A. filiculoides* could be used now as a monocrop basal fertilizer before transplanting of rice. This should be easy to popularize for the late winter or early spring rice crops.

Before azolla is used in rice, however, it should be tested under local conditions. As was stated, keeping azolla alive throughout the year and finding ways to multiply it for field use are the most important steps in beginning a program. The next step is testing under local conditions to find ways to fit it into the existing production system. Use as a basal fertilizer before transplanting is probably easiest, but if the crop cycle doesn't allow time to grow an azolla green manure crop between rice crops, then it will be necessary to grow it as an intercrop. In that case the rice must be grown in rows so that incorporation of the azolla can be done. This is just an illustration of some of the considerations to be dealt with in using azolla in agricultural production systems.

CONSTRAINTS TO THE DEVELOPMENT AND IMPLEMENTATION OF AZOLLA TECHNOL0GY

Scientific Constraints

The global azolla research effort is disorganized and much of the work is repetitious and often useless. Certain problem areas, such as those involving agricultural engineering, have been ignored. Much of the support is going to finance esoteric work, while many of the people doing the research have little understanding of the problems that prevent azolla's widespread use by peasant farmers. Much of the work is involved in trying to improve laboratory specimens of azolla, while the vast differences in wild varieties remain unexamined.

Many of the problems preventing the widespread use of azolla require a multidisciplinary research approach, but so far azolla research has been cloistered into individual departments, even in the international institutes.

Funding agencies can assist in ensuring that azolla research will be directed toward real problems and needs by requiring multidisciplinary, linked efforts that focus on use of azolla on farms. This does not mean that basic research will be precluded, but it will ensure that practical, mission-oriented research will not be neglected.

Environmental Constraints

Water is the primary environmental constraint to the cultivation of azolla. Azolla is a freefloating aquatic fern and is therefore limited to locations that have an abundant, stable water supply during field cultivation.

Temperature and humidity: For practical purposes, azolla survives within the water temperature range of O to 40°C; beyond this range, death will result, For adequate growth during field cultivation, the daytime water temperature should stay within the range of 15° to 35 ‘C. Humidity and temperature interact in their effect on azolla. Very high humidity and high temperature or very low humidity and low temperature are both detrimental to the growth of azolla.

pH: The pH of the paddy water plays an im portant part in the ability of azolla to survive Besides directly affecting the growth of azolla, pH also affects the availability of nutrients, especially phosphorus. Low pH and high pH can cause formation of insoluble compounds that tie up available phosphorus; the phosphorus in such insoluble compounds is unavailable to azolla. Azolla grows best within a pH range of 5 to 7 and can survive a range of 3.5 to 10.

Available nutrients: Azolla growth depends on an adequate supply of essential elements in the water or in the surface layer of mud. These elements must also be relatively balanced, Usually the addition of phosphorus and sometimes potassium is all that is necessary to ensure good growth.

Cultural and Economic Constraints

For most farmers, azolla cultivation would be an entirely new way of using green manure. The idea of using an aquatic plant for such purposes is not part of most agricultural heritages, Farmers in tropical Asia traditionally have grown upland legume crops, such as milk vetch or lentils (as a cash crop), after harvesting the monsoon rice crop. Most have never grown an aquatic green manure, and many have rarely grown a legume that is not a food or forage crop. To some, especially the hungry, growing a crop that is to be plowed under as a green manure may seem impractical.

Azolla can be used as a forage for pigs, ducks, and fish. However, the raising of swine, ducks, and fish is uncommon in some places. Also, it is generally believed, although untested, that cattle and water buffalo will not eat azolla.

The year-round cultivation of azolla is more complex than the cultivation of rice. Without support, many poor uneducated rice farmers probably would not or could not grow azolla, Diligent rice farmers, such as those in Nepal or Thailand, probably could master azolla cultivation techniques, just as farmers in China and Vietnam have. As a result of unfavorable land ownership patterns, low grain prices, and other social or economic difficulties, some peasant rice farmers do little more than haphazardly plant their fields and then wait for harvest time. For them, meticulous farming does not yield sufficient benefits to their family, Furthermore, transplanted rice in some parts of Asia is not planted in rows, a necessary measure for azolla to be incorporated as a basal fertilizer.

Also, many farmers who could not be convinced to use nitrogen fertilizer in the 1960s when it was inexpensive, will be unlikely to cultivate azolla. The exceptions might be peasant farmers who want to improve their crop yields but do not have the capital to purchase nitrogen fertilizers. Also, farmers who have given up using nitrogen fertilizer because of the high cost might be convinced to use azolla as long as they can afford the cash outlay for relatively small amounts of phosphorus fertilizer and pesticides. They would have to purchase about 100 kg of single superphosphate to grow one hectare of azolla for 4 to 5 weeks. If properly applied, the phosphorus would result in as much nitrogen as 500 kg of commercial ammonium sulfate fertilizer,

Azolla cultivation could significantly reduce the fertilizer input costs of raising high yielding rice crops, but would still require the purchase of certain inputs, especially phosphorus fertilizer. Farmers unable to obtain these inputs would probably find it difficult or impossible to raise azolla.

Political Constraints

The widespread cultivation of azolla is found only in Communist countries. Azolla was cultivated in both China and Vietnam before the present governments came to power, but on only a small fraction of the area that azolla covers today. Analyzing the elements of this situation is difficult because the cultivation of azolla in China and Vietnam cannot be compared to its cultivation in countries with different political systems. Because azolla cultivation is just being introduced to farmers elsewhere, there has been insufficient time for other countries to develop successful azolla programs that are in line with their political systems.

Even without an adequate comparison, it is obvious that the successful azolla programs in China and Vietnam owe a considerable amount to the way their farming systems are organized. The commune and cooperative organizations of these countries that use azolla have highly trained azolla teams, whose sole function is to ensure the success of azolla cultivation. Training workshops to learn the newest techniques are held annually from the national level down to the local azolla team level. In addition, every level regularly publishes pamphlets about the practical applications of azolla.

The higher levels of the Chinese and Vietnamese systems can be transferred with minor modifications to other countries, but not the lower local levels. Most governments do not have the power to enforce their will on independent peasant farmers as effectively as China and Vietnam can influence their communes and cooperatives. Nor can a peasant farmer be expected to master all the intricacies of successful azolla cultivation that are known by a highly trained commune azolla team.

THE EFFECT OF THE IMPLEMENTATION OF AZOLLA TECHNOLOGY ON THE NEED FOR INPUTS

capital

Capital requirements for azolla cultivation are quite small. For most farmers, only a small amount of phosphorus fertilizer, often no more than would be required for the rice crop, and pesticides to protect the azolla from pests and diseases are all that will be required.

Farm Labor

In essence, the cultivation of azolla exchanges labor for nitrogen fertilizer. The present azolla technology is based on the Chinese and Vietnamese models and thus is extremely labor intensive. In fact, the cultivation of azolla cannot be adopted by countries with mechanized rice farming systems until new capital intensive technology is developed.

Adoption of azolla cultivation by a developing country can only increase the demand for farm labor, especially when nursery stocks are being multiplied and during field cultivation. In addition, a few workers will have employment year-round because of the need to maintain azolla nurseries during the off season.

Rice requires about 20 kg of nitrogen per ton of the harvested crop. About half of this is recycled into the soil in the crop residue; therefore about 10 kg of nitrogen is removed per ton of harvested grain. A 6 ton rice harvest removes about 60 kg of nitrogen from the soil, equivalent to 300 kg of ammonium sulfate fertilizer. If azolla was substituted for ammonium sulfate, nearly all of the money required to purchase the 300 kg of ammonium sulfate fertilizer could theoretically be used to pay farm labor to grow azolla, or to gain a greater return on family labor.

Azolla appears to offer special opportunities for small farms, particularly family farms with abundant labor. Conversely, suitable azolla technology for large mechanized farms is not available.

Azolla is used successfully on large communes in China, but the organization of these communes is difficult to relate to family farms.

Land

The land required for azolla cultivation mainly is related to nursery and field multiplication. For overwintering or oversummering, very small protected greenhouse or field areas are required, more in the area of small garden plots than large field areas. However, when azolla multiplication for field inoculation is to be achieved, much more land is required. Perhaps as much as 10 percent of the rice crop area to be inoculated is a good estimate of the land area needed for azolla field multiplication. This land is not tied up permanently, however, but it will be devoted to azolla multiplication for a month or so prior to inoculation.

For farming systems that use azolla as a basal, soil incorporated green manure before the rice crop, all of the land to be planted into rice and fertilized with azolla will need to be devoted to azolla cultivation for about a month prior to transplanting.

In situations where azolla is used as a soil-incorporated, top-dressed green manure or as an unincorporated intercrop with rice, no land will be required to be devoted solely to azolla, except for the inoculation nurseries.

CONCLUSIONS

Azolla is being used as a primary source of nitrogen on an increasing land area in transplanted rice crops in China and Vietnam. The largest use of azolla in these countries is in the spring rice crop, mostly as a monocrop grown before rice as a basal, soil-incorporated green manure. Less is used as an intercropped top-dressing green manure in transplanted rice that is planted in rows.

Use of azolla in the summer rice crop is hampered by high water temperatures and heavy pest attack. A search for suitable temperature-tolerant species or varieties could have high payoff.

Species used in agriculture today are: *A. pinnata, A. pinnata* var. *imbricata* (sometimes referred to as *A. imbricata,* and *A. filiculoides. A. pinnata* and *imbricata* have been used for a long time in China and Vietnam, but their susceptibility to high temperatures and pest attack makes them suitable only for spring and some fall rice crops. *A. filiculoides* has just begun to be used widely in China, especially in areas where-because of its cold tolerance— it can be grown in late winter and early spring as a green manure for early spring rice. Although *A. filiculoides* has proved useful in China because of its cold tolerance, it is even less tolerant of high water temperatures (above *250* to *270 C)* than *A. pinnata*. What is needed, then, is an azolla that can tolerate high summer temperatures, up to **400** C or so. *A. microphylla,* collected by T. Lumpkin in the Galapagos Islands, shows promise of becoming a suitable summer green manure for central China and a winter green manure in south China.

There is a great need to collect and characterize species and varieties of azolla extant in nature. This work is of the highest priority. The potential worth of *A. microphylla* in China has already been mentioned. However, it may be useful to point out that *A. nilotica,* collected by T. Lumpkin in the Sudan, has shown the highest nitrogen fixation of any azolla studied. Lumpkin was only able to collect three specimens of *A. nilotica,* yet many more strains and types are available in the Nile Basin and these should be collected and characterized as soon as possible.

All species could prove useful. For example, varieties of *filiculoides* look promising now for use in certain agricultural situations. The same can be said about *microphylla, imbricata, pinnata,* and *caroliniana.*

Research programs should stress multidisciplinary approaches, with close links between

38-846 0 - 85 - 5

institutions. Both tropical and temperate farming systems should be emphasized, but these programs should be centered in different places. Both temperate and tropical research programs should be linked, and should cooperate in collection and characterization of species and varieties. The tropical program should focus on using azolla in tropical farming systems, notably small peasant farms, and the temperate program should focus on capital intensive mechanized rice production systems. An international meeting should be held that will have as its major agenda item the setting of international research priorities for azolla. The primary focus of research programs should be to find a useful role for azolla in farming systems. Basic research should not be neglected, but the potential usefulness of azolla is too great to delay its wider use in agriculture through emphasis on more esoteric topics at the expense of applied research.

References

1. Dolbert, Frands, DANIDA, personal communication, 1980.
2. Food and Agriculture Organization, *China: Azolla propagation and small-scale biogas technology,* Food and Agriculture Soils Bull. No. 41, FAO, Rome, 1978.
3. Guandong Academy of Agricultural Science, *Red Azolla* (People's Publisher, Guandong (in Chinese), 1975).
4. Guandong Bureau of Agriculture, *Questions and Answers Concerning Azolla Cultivation* (People's Publisher, Guandong (in Chinese), 1975),
5. International Rice Research Institute, *International Bibliography on Azolla,* IRRI (Los Ganos, Philippines, 1979), 66 pp.
6. Lumpkin, T. A., "Environmental Constraints to Azolla Cultivation, " *Proc. Second Review Meeting I.N.P.U.T.S. Project* (Honolulu, Hawaii, May 18-19, 1978), pp. 175-180.
7. Lumpkin, T. A, and Plucknett, D. L., "Azolla: Botany, Physiology, and Use as a Green Manure," *Econ. Bet. 34(2): 111-153, 1980.*
8. Moore, A. W., "Azolla: Biology and Agronomic Significance, " *Bet. Rev.* **35: 17-35, 1969.**
9. Peters, G. A., "The *Azolla-Anabaena* Symbiosis," In: Alexander Hollaender (cd.), *Genetic Engineering for Nitrogen Fixation* (Plenum Press, New York and London, 1977), pp. 231-258.
10. Singh, P. K., "Use of Azolla in Rice Production in India," In: *Nitrogen and Rice* (International Rice Research Institute, Philippines, 1980), pp. 407-418.
11. Talley, S. N., and Rains, D. W., "Use of Azolla in North America, " In: *Nitrogen and Rice* (International Rice Research Institute, Philippines, 1980), pp. 419-431.
12. Vo, M. K. am-l Tran, Q. T., *Beo Hoa Dau (Azolla)* (Agricultural Publisher, Hanoi, 1970), 171 pp.
13. Watanabe, I., Espinas, C. R., Berja, N. S., and Alimagno, V. B., "Utilization of the *Azolla-Anabaena* Complex as a Nitrogen Fertilizer for Rice," International Rice Research Institute, Res. Paper Ser. No, 11, 1977.
14. Zhejiang Academy of Agricultural Science, *Cultivation, Propagation and Utilization of Azolla* (Agricultural Publishing House, Beijing (in Chinese]. 1975).