NITROGEN-FIXATION TECHNOLOGY FOR INCREASED AGRICULTURAL SUSTAINABILITY

W.A. Rice and P.E. Olsen
Research Station, Agriculture Canada
Beaverlodge, Alberta

Abstract

The advent of the world energy crisis in 1973 aroused interest in the potential of nitrogen fixation for increasing agricultural production. Since then, sustainable agriculture has become the focus of attention. Sustainable agriculture involves design and management of procedures which work with natural processes to conserve resources, and minimize waste and environmental damage, while maintaining farm profitability. As agriculture moves towards greater sustainability, the potential role of nitrogen-fixation processes increases. As a result, the agronomic significance of nitrogen fixation has generated renewed scientific excitement in this area of microbial-plant interaction. A number of significant advances in applied nitrogen-fixation technology have been made: improved rhizobial delivery systems, increased nitrogen-fixation capacities, greater yield and improved quality of legumes, and better definition of the role of nitrogen fixation in N cycling. Shifts in agricultural sustainability that involve these improved nitrogen-fixation technologies require continued research efforts to assess the levels of resource conservation, impacts on the environment and the economic consequences.

Introduction

The International Conference on Soil Quality in Semiarid Agriculture which was held June, 1989, in Saskatoon,in part consisted of six workshops in which participants discussed soil quality under six different problem areas. These areas were soil structure, nutrient availability, chemical additions, water-use efficiency, chemical balance and organic matter. In all six workshop reports, nitrogen fixation and/or legume crops were stressed as important for increasing N input and improving soil quality. The attention which symbiotic nitrogen fixation in legumes has attracted not only points to its agronomic significance but also to the scientific excitement which this area of microbial-plant interaction has generated in research using new biotechnological methods. In recent years biotechnology has added to the potential benefit that can be derived from nitrogen-fixation research.

The world of science and technology is changing rapidly and is increasingly being influenced by public opinion and ethics. The advent of the world energy crisis in 1973 aroused interest in the potential of nitrogen fixation for increasing agricultural production. Since then the energy crisis seems to have moved somewhat into the background, and soil conservation and sustainable agriculture have become the focus of attention. The fact that nitrogen fixation research continues to survive through these changes and interest in nitrogen-fixation processes in agricultural systems remains high demonstrates its importance. A more detailed analysis of the situation is required in order to appreciate the significance of the nitrogen fixation process and its attendant research needs for agriculture in western Canada.

Global Perspective

On a global basis, the size of the nitrogen fixation flux has been estimated to be 2.6 times that of fertilizer N application (Paul and Clark, 1989). Symbiotic nitrogen fixation is about 2.5 times that of asymbiotic plus associative fixation. However, N losses from denitrification, leaching and erosion are about 1.3 times that of nitrogen fixation inputs into the global terrestial system.

The ability to measure the flux of N through the soil-plant system is still developing and requires further refinements in techniques to delineate microbial biomass and active N pools, but the present information provides an indication of the relative size of the nitrogen fixation flux. On this basis one could argue that there is need to pursue research in nitrogen fixation in order to increase the amount of total nitrogen fixation relative to N fertilization, and to increase asymbiotic/associative fixation relative to symbiotic fixation.

Since we are considering this topic from an agricultural perspective, we should be aware of the relative inputs by nitrogen fixation in agricultural and non-agricultural land areas. Nitrogen fixation by legume crops accounts for 25% of the total terrestial nitrogen fixation (Paul and Clark, 1989). This amount is substantial in terms of the absolute amount and suggests that the potential for increased nitrogen fixation in legume crops should be explored if more efficient N inputs for agricultural systems is a major objective.

Nitrogen-fixation research is immensely important because of the practical implications stemming from the World's population explosion. The N-contents of the the World's agricultural produce must increase in proportion to the predicted doubling of the population within the early decades of the next millenium. To obtain such an increase in N-output, the N-input into the World's arable soils must also increase. In general it is agreed that both increased biological and chemical N-inputs are essential over the next several decades.

Nitrogen Fixation and Sustainable Agriculture

As pointed out earlier, a recent international conference emphasized the role of nitrogen fixation in maintaining soil quality and the need for continued research to increase nitrogen input through fixation. The need is as great in Canada as in any other part of the world. National social conscience has brought us to a serious consideration of the concepts of soil conservation and, more broadly, sustainable agriculture, and both these concepts are important driving forces in research objectives, on technology transfer initiatives and in the implementation of soil and crop management practices. The process of nitrogen fixation has important bearing on these concepts.

Sustainable agriculture involves design and management of procedures which will enhance the environmental quality of soil and associated water, provide for basic human food and fibre needs, maintain or improve farm profitability, and enhance the quality of life for both the farms and society as a whole (Ecological Agriculture Projects, 1989; Rennie, 1989). The major schools of thought in sustainable agriculture have been classified according to operating principles based on concepts of efficiency, substitution and redesign. The efficiency concept involves a reduction in resourse use and associated negative environmental impact, and may result in a reduction of input expenses. Substitution of safe products and practices (eg. biocontrol agents) further enhances efficient resource utilization and reduces environmental damage. The systems which focus on redesign are the most sophisticated; they utilize crop rotations which minimize tillage, use legumes and green manures, prevent pest and disease outbreaks and recycle resources to the greatest extent possible, meaning that little is wasted and few pollutants are generated.

Rennie (1989) has defined sustainable agriculture for the Palliser Triangle of the Prairies in terms of on-the-farm practices. In his definition, sustainable agriculture includes: cropping systems with maximum water use efficiency; minimal or no-till summerfallow when required; simple crop rotations dominated by wheat, with minor crops including coarse grains, grain legumes and oilseeds; use of disease and pest resistant varieties; plant and animal wastes used as soil building amendments; and maintainence of a balance between mechanical and chemical weed control. This concept applies to the rest of the Prairies with some modifications. For example, in the Peace River region crop rotations become more sophisticated with the extensive use of other cereals, forage and grain legumes and oilseed crops. The inclusion of legume crops in crop systems is an integral part of sustainable agricultural development.

As agriculture moves from low to high sustainablity, the potential role of nitrogen-fixation processes increases. Any shift in sustainability that involves nitrogen fixation, such as increased use of legumes in rotations, will require continued research efforts to assess the level of conservation of resources, the impact on the environment and the economic consequences.

The Challenge

In order to meet the challenge for maximum effect of nitrogen fixation in sustainable agriculture, we must consider more specific aspects of the fixation process. An example from the past is the legume inoculant and preinoculated seed products testing program presently in effect in Canada. Canada is envied for its progressive testing program with quality standards that are among the highest in the world. This program came about because of a recognition by producers, extension personnel and researchers that something had to be done about inoculant quality. Nitrogen-fixation research programs at a number of Agriculture Canada Research Stations in the early 1970's applied the networking concept to do the research to develop uniform methodology and establish inoculant quality standards that satisfied the stress conditions imposed by the soil and climatic conditions of the various regions. This program is the basis for ensuring that textbook knowledge becomes field reality.

A number of significant advances in nitrogen-fixation technology have been made which will assist in the development of management practices for conserving soil organic matter and implementing efficient crop production systems adapted to diverse soil and climatic conditions. These include the following:

1. improved rhizobial delivery systems
2. increased nitrogen-fixation capacities, particularly under stress conditions
3. greater yield and improved quality of legumes
4. better definition of the role of nitrogen fixation in N cycling.

The type of rhizobial delivery system used has important effects on the ability of the inoculant strain to induce nodulation in the presence of competing strains. Systems which bind the inoculant to the seed with stickers or by means of pelleting processes have been found to increase nodulation and the proportion of nodules inhabited by the the inoculant strain (Rice and Olsen, 1983). Application of granular inoculants in the seed row for crops such as soybeans has proved to be beneficial (Brockwell et al., 1980). Recent work has shown that granular inoculants used with alfalfa significantly incresaed nodule weight and forage yield when the indigenous *R. meliloti* population was low (Table 1), but had little effect when the indigenous population was high (Table 2). These results indicate that there is still potential for improving rhizobial delivery systems for alfalfa.

TABLE 1. FORAGE YIELD, NUMBER OF NODULES, WEIGHT OF NODULES AND STRAIN OCCUPANCY OF NODULES OF ALFALFA INOCULATED BY TWO METHODS AND GROWN ON SOIL WITH LOW INDIGENOUS POPULATIONS OF *R. meliloti*

	YIELD KG DM/HA	NODULES PER PLANT	NODULE WT. MG/PLANT	OCCUPANCY % INOC. STRAIN
UNINOCULATED	3574	0.4	7.9	0
POWDER ON SEED	4308	0.8	18.3	46
GRANULAR IN SEED ROW	6683	5.0	90.4	97

BLACK SOLOD SOIL, pH 5.8, 100 INDIGENOUS RHIZOBIA/G

There are numerous examples of increased nitrogen-fixation through the use of improved strains of rhizobia. Improved nitrogen-fixing performance by *R. meliloti* has been achieved by selecting for low pH tolerance (Rice, 1982), superior strains of *R. leguminosarum* were identified which increase nitrogen fixation by lentil (Bremer et al., 1990) and a strain of *Bradyrhizobium*

TABLE 2. FORAGE YIELD, NUMBER OF NODULES, WEIGHT OF NODULES AND STRAIN OCCUPANCY OF NODULES OF ALFALFA INOCULATED BY TWO METHODS AND GROWN ON SOIL WITH HIGH INDIGENOUS POPULATIONS OF R. meliloti

	YIELD KG DM/HA	NODULES PER PLANT	NODULE WT. MG/PLANT	OCCUPANCY % INOC. STRAIN
UNINOCULATED	4419	0.8	24.8	1
POWDER ON SEED	4670	0.9	31.1	36
GRANULAR IN SEED ROW	5157	5.7	49.2	95

BLACK SOLOD SOIL, pH 5.8, 100,000 INDIGENOUS RHIZOBIA/G

japonicum has been shown to increase yield of soybeans in field soils with no indigenous B. japonicum (Veeraraghavaiah and Hume, 1989). Although in recent years there has been considerable interest in genetic engineering of rhizobia to increase nitrogen fixation, the occurrence of naturally selected strains with improved nodulating and nirogen-fixing ability is largely unexplored.

Another area that has not been fully explored is the adaptation of legume plants with more desirable crop characteristics to a wider array of stress conditions. Moisture stress is the one environmental characteristic that pervades throughout much of the Prairies and limits yield as well as the range of legumes that can be grown. Field experiments conducted by Biederbeck and Looman (1985) under the severe drought conditions of 1984 in southwestern Saskatchewan showed that chickling vetch had superior nodulating ablity (Figure 1) and water use efficiency (Table 3) as compared to three other annual legume crops. Also, controlled environment studies have shown that there are crop differences in nitrogen fixation (acetylene reduction) with increasing plant water potentials (Smith et al., 1988). These results idicate the genetic diversity in legume plants and suggest that there is potential for application of molecular genetics in advancing the range of adaptation of crops with desirable yield and quality characteristics.

Considerable advances have been made with simulation models to describe soil organic matter turnover (ie. C and N turnover) over long periods of time, and in establishing a more precise fit between the models and observed experimental data (Paul and Clark, 1989). However, we need a better definition of the role of nitrogen fixation in N and C cycling. It is now possible to accurately estimate the amount of nitrogen fixation in various legume crops in the field (Rennie, 1985), and there appears to be considerable consistency between different agroclimatic areas in the amounts of recovery of legume N recovered in subsequent ceral crops (Table 4). With between 10 and 25% of the legume N recovered in the first crop and only about 2% in the second crop (Janzen et al., 1989) there is a large proportion of the legume green manure-N contributing to the long-term organic N reserves in the soil. Even with potential volatilization loss of up to 14% of the N from green manuring (see Janzen and Biederbeck in this Proceedings) the proportion of N remaining is considerable. This was confirmed by observations made on the Breton plots in Alberta, where organic matter, humic acid, total-N and hydrolysable-N contents of a Grey Luvisolic soil were increased after long term rotations involving legume hay crops (Table 5). However, there is still need for more information on the long term contribution of the N from legume origin to C and N turnover and subsequent availablity of N to crops.

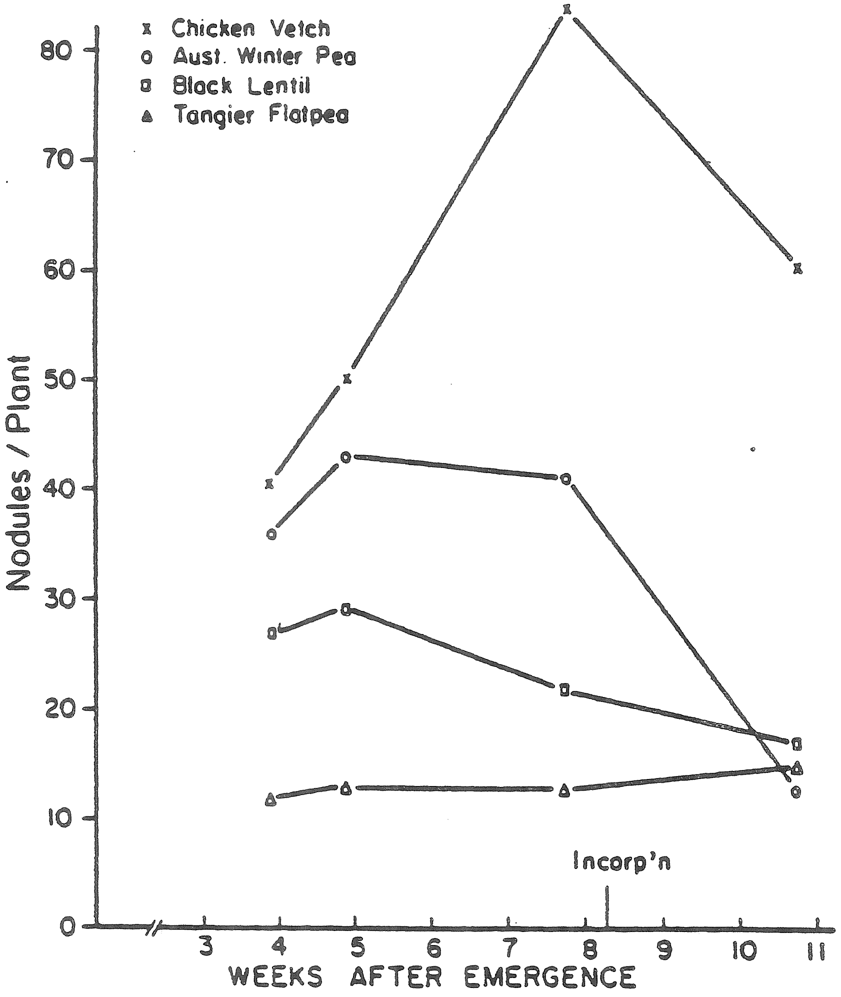

Figure 1. Nodulation of inoculated annual legumes during the severe drought conditions of the summer of 1984, at Swift Current, Sask. (Adapted from Biederbeck and Looman, 1985)

TABLE 3. WATER USE EFFICIENCY OF NITROGEN FIXATION BY GREEN MANURE LEGUMES

CROP	MG N FIXED /KG WATER USED
CHICKLING VETCH	28
BLACK LENTIL	17
AUSTRIAN WINTER PEA	12
TANGIER FLATPEA	10

ADAPTED FROM BIEDERBECK AND LOOMAN, 1985

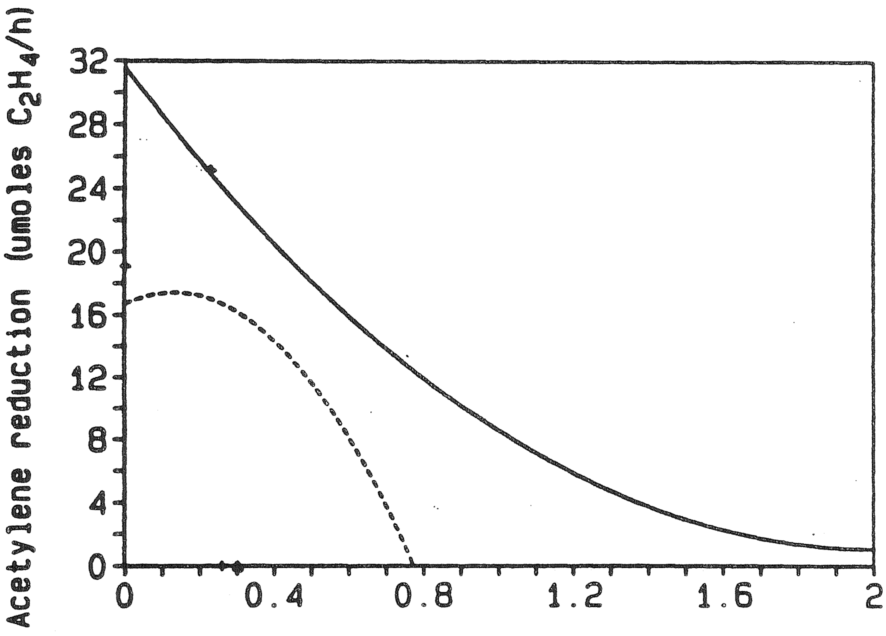

Figure 2. Change in acetylene reduction activity with change in plant water potential for white bean (--------) and soybean (————) plants in a controlled environment drying cycle experiment. (Adapted from Smith et al., 1988)

TABLE 4. RECOVERY OF GREEN MANURE-N IN THE SUBSEQUENT CEREAL CROP

	% OF ADDED GREEN MANURE-N
CANADA (JANZEN ET AL.)	9 - 27
FINLAND (MUELLER ET AL.)	6 - 25
AUSTRALIA (LADD ET AL.)	11 - 28

(ADAPTED FROM JANZEN ET AL., 1989)

TABLE 5. EFFECT OF CROPPING SYSTEMS ON ORGANIC MATTER, HUMIC ACID, TOTAL-N AND HYDROLYSABLE-N IN THE BRETON PLOTS (KHAN, 1970; KHAN, 1971)

ROTATION	ORGANIC MATTER (%)	HUMIC ACID (g/100g)	TOTAL-N (%)	HYDROLYSABLE-N (% of total-N)
GRAIN-FALLOW (1)	2.15	0.407	0.117	75.1
GRAIN-LEGUMES (2)	2.57	0.487	0.146	79.0

(1) 2-YEAR WHEAT-FALLOW ROTATION
(2) 5-YEAR WHEAT-OATS-BARLEY-LEGUME HAY-LEGUME HAY ROTATION

Conclusion

Research on nitrogen fixation provides for a multidisciplinary approach of tackling present and future challenges of increasing the level of sustainability in agriculture. Biochemists, geneticists, physiologists, microbiologists, plant molecular biologists, agronomists, etc. are all able to develop their specialties in relation to the demands for more information on the subject as a whole. In particular, there is need for developing greater nitrogen-fixation capacities in legumes (plant and rhizobial genetics) and for understanding the role of fixed N in both C and N cycling in agroecosystems.

Any research is incomplete until the resulting scientific information and technology have been transferred to the client. We must ensure that the significance of the current research on nitrogen fixation is well known to industry, farm producers, environmentalists and policy makers.

References

1. Biederbeck, V.O. and J. Looman. 1985. Growth of annual legumes for soil conservation under severe drought conditions. Pages 298-311 in Conservation For The Future, Proceedings of the Soils and Crop Workshop, University of Saskatchewan, Saskatoon.

2. Bremer, E., C. Van Kessel, L. Nelson, R.J. Rennie, and D.A. Rennie. 1990. Selection of Rhizobium leguminosarum strains for lentil (Lens culinaris) under growth room and field conditions. Plant Soil 121: 47-56.

3. Brockwell, J., R.R. Gault, D.L. Chase, F.W. Hely, M. Zorin and E.J. Corbin. 1980. An appraisal of practical alternatives to legume seed inoculation: field experiments on seed bed inoculation with solid and liquid inoculants. Aust. J. Agric. Res. 31: 47-60.

4. Ecological Agricultural Projects. 1989. An introduction to sustainable agriculture. Agriscience (September, 1989): p 3-5.

5. Janzen, H.H., J.B. Bole, V.O. Biederbeck and A.E. Slinkard. 1989. Contribution of green manure to the N nutrition of subsequently grown wheat as determined by 15N techniques. Pages 211-221 in 26th Annual Alberta Soil Science Workshop Proceedings, University of Alberta, Edmonton.

6. Khan, S.U. 1970. Humic acid fraction of a Gray Wooded soil as influenced by cropping systems and fertilizers. Geoderma 3: 247-254.

7. Khan, S.U. 1971. Nitrogen fractions in a gray wooded soil as influenced by long-term cropping systems and fertilizers. Can. J. Soil Sci. 51: 431-437.

8. Paul, E.A. and F.E. Clark. 1989. Soil microbiology and biochemistry. Academic Press, Toronto. 273 pp.

9. Rennie, D.A. 1989. Managing soil conservation. Agriscience (December, 1989): p 8-9.

10. Rennie, R.J. 1985. Nitrogen fixation in agriculture in temperate regions. Pages 659-665 in H.J. Evans, P.J. Bottomley and W.E. Newton (Eds.), Nitrogen Fixation Research Progress, Proceedings of the 6th International Symposium on Nitrogen Fixation, Matinus Nijhoff Publishers, Dordrecht.

11. Rice, W.A. 1982. Performance of Rhizobium meliloti strains selected for low-pH tolerance. Can. J. Plant Sci. 62: 941-948.

12. Rice, W.A. and P.E. Olsen. 1983. Inoculation of alfalfa seed for increased yield on moderately acid soil. Can.J. Soil Sci. 63: 541-545.

13. Smith, D.L., M. Dijak and D.J. Hume. 1988. The effect of water deficit on nitrogen (acetylene) fixation by white bean and soybean. Can. J. Plant Sci. 68: 957-967.

14. Veeraraghavaiah, R. and D.J. Hume, 1989. Performance of early-maturing soybeans with strains of B. japonicum and R. fredii. p41 in 12th North American Symbiotic Nirogen Fixation Conference Proceedings, Iowa State University, Ames, Iowa.