FINAL REPORT

OF THE

FAO/IAEA CO-ORDINATED RESEARCH PROJECT

ON

THE USE OF NUCLEAR AND RELATED TECHNIQUES FOR EVALUATING THE AGRONOMIC EFFECTIVENESS OF PHOSPHATE FERTILISERS, IN PARTICULAR ROCK PHOSPHATES (D1-50.03)

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# TABLE OF CONTENTS

1. Introduction .................................................................................................................. 1

2. The Co-ordinated Research Project ............................................................................... 2
   A. Title ............................................................................................................................... 2
   B. Project duration .......................................................................................................... 2
   C. Rationale ...................................................................................................................... 2
   D. Objectives .................................................................................................................... 2
   E. Description ................................................................................................................... 2
   F. Major achievements/outputs, and impact ................................................................... 2
   G. Overall implementation ............................................................................................... 2

3. The Fourth and Final Research Co-ordination Meeting .................................................. 5

4. Conclusions and Recommendations ............................................................................ 7
   4.1 P Availability Studies, including Environmental Issues ........................................... 7
      4.1.1 Conclusions on P availability ............................................................................. 7
      4.1.2 Recommendations on P availability .................................................................. 7
      4.2.1 Conclusions on Environmental Issues ................................................................. 7
      4.2.2 Recommendations on Environmental Issues ...................................................... 7
   4.2 Agronomic Effectiveness of P fertilizers ................................................................... 13
      4.2.1 Conclusions ....................................................................................................... 13
      4.2.2 Recommendations ............................................................................................. 13
   4.3 Practical recommendations for applications of P fertilizers ..................................... 14
      4.3.1 Conclusions ....................................................................................................... 14
      4.3.2 Recommendations ............................................................................................. 14
   4.4 Phosphate Studies in Eastern Europe ........................................................................ 16
      4.4.1 Introduction ....................................................................................................... 16
      4.4.2 Work programme ............................................................................................... 16
      4.4.3 Results obtained ................................................................................................. 16
      4.4.4 Conclusions ....................................................................................................... 16

Annexes

<table>
<thead>
<tr>
<th>Annex</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annex A</td>
<td>Programme</td>
</tr>
<tr>
<td>Annex B</td>
<td>List of Participants</td>
</tr>
<tr>
<td>Annex C</td>
<td>Summaries of Work Done During the CRP</td>
</tr>
<tr>
<td>Annex D</td>
<td>List of Publications</td>
</tr>
</tbody>
</table>
1. Introduction

Soils in developing countries are often deficient in available P, and therefore require inputs of P fertiliser for optimum plant growth and production of food and fibre. Due to economic considerations, the cost of applying imported or locally produced water-soluble P fertilisers is often more expensive than utilising indigenous phosphate rock. Phosphate rocks show large differences in their suitability for direct application and several factors influence their capability to supply phosphorus to crops. Therefore, quantifying the P availability of soils amended with phosphate rocks in a variety of crop management and environmental conditions in developing countries is imperative for making recommendations on the best type and rate of P fertiliser sources for maximum agronomic and economic benefits. P-32 isotope techniques are very useful for such studies.

The background situation of phosphate research and the topics to be investigated using isotope techniques were critically examined in a Consultants Meeting held at the IAEA Headquarters, Vienna, Austria, from 10 to 12 May 1993. For detailed information please refer to IAEA Report CT-1112.

Based on the recommendations of this Consultants’ Meeting, the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture with the generous support of the French Government decided to implement the Co-ordinated Research Project (CRP) on "The Use of Nuclear and Related Techniques for Evaluating the Agronomic Effectiveness of Phosphate Fertilisers, in particular Rock Phosphates" (D1.50.03).

The First Research Co-ordination Meeting (RCM) of the CRP was held at the IAEA Headquarters in Vienna, from 1 to 5 November 1993. Dr. F. Zapata was the Scientific Secretary of the meeting. (Refer to IAEA Report D1-RC-542.1).

The Second Research Co-ordination Meeting (RCM) was convened in the "Centre de Cooperation Internationale en Recherche Agronomique pour le Developpement" (CIRAD), Montpellier, France, from 24 to 29 April 1995. Dr. Truong Binh was the local organizer of the meeting. (Refer to IAEA Report D1-RC-542.2).

Thanks to the generous support of the French Government, 6 new contracts were awarded in 1996 to scientists from Eastern Europe, i.e., Belarus, Hungary, Lithuania, Poland, Romania and the Russian Federation.

In 1996, a Co-operation Agreement between the IAEA and the World Phosphate Institute (IMPHOS) was established to support the field networking activities of the project and to contribute to the dissemination of the information generated, thus increasing the potential impact of the project.

The Third RCM was held in the IAEA Headquarters, Vienna, 17-21 March 1997. Dr. F. Zapata served as Scientific Secretary for the meeting. Please refer to the IAEA Report D1.RC-542.3.
This final report describes the Fourth and Final RCM of the CRP which was held in Vienna, 16-20 November 1998. It also contains a full description of the project and the conclusions and recommendations of the CRP. The programme of the meeting, list of participants, summaries submitted by the participants list of publications are included as annexes.

2. The Co-ordinated Research Project

A. Title: FAO/IAEA CO-ORDINATED RESEARCH PROJECT on "The Use of Nuclear and Related Techniques for Evaluating the Agronomic Effectiveness of Phosphate Fertilizers, in particular Rock Phosphates"

B. Project duration: 5 years (1993-1998)

C. Rationale

1. Soils in developing countries are often deficient in available P, and therefore require inputs of P fertilizers for optimum plant growth and production of food and fibre.

2. Phosphate fertilizer recommendations for developing countries would need to take into consideration cost for procurement and availability of fertilizer supplies within the context of Integrated Plant Nutrition Systems which FAO/IAEA and many others are actively supporting. In the case of P fertilization this would imply developing an effective and economic phosphate management programme, in which the use of rock phosphate deposits will play a key role.

3. Rock phosphate deposits have been found in many developing countries of Asia, Africa and Latin America. Direct application of finely ground rock phosphate, including indigenous phosphate deposits where possible, is among the cheapest means of supplying P to crops in tropical acid soils.

4. Some rock phosphates are better (more reactive) than others, and several factors will influence their capability to supply phosphorus to crops. Also, quantifying the P availability of soils amended with rock phosphates in a variety of crop management and environmental conditions is imperative for making appropriate fertilizer recommendations to obtain maximum agronomic and economic benefits. P-32 isotope techniques are useful for such studies.

D. Objectives

1. To assess the initial available soil P status and its changes when amended with rock phosphate products and water-soluble P fertilizers in a variety of agro-ecosystems using conventional (chemical) and isotopic techniques.

2. To quantitatively evaluate the uptake and use of P fertilizers, in particular rock phosphate-based products by the crops under a variety of soil and climatic conditions.
Thus, the project aims at evaluating the agronomic effectiveness of natural rock phosphate deposits and where necessary, means of enhancing their effectiveness.

3. To obtain agronomic and economic recommendations on the use of P fertilizers, in particular rock phosphate-based products.

E. Description

1. The research network comprises 10 research contract holders from the following developing countries: Brazil, Chile, China, Cuba, Indonesia, Kenya, Malaysia, Romania, Thailand, and Venezuela, and 6 agreement holders from USA (IFDC and University of Kentucky), France (CIRAD and CEN-Cadarache), Australia (CSIRO) and Spain (CSIC).

Five new contractors from Belarus, Hungary, Lithuania, Poland, and Russia have been included thanks to the generous support of the French Government.

2. In addition to conventional techniques, the following P-32 isotope techniques are used: P-32 isotopic exchange kinetics for objectives (1) and (2), P-32 isotope dilution techniques for objective 2.

3. Essential features of the project include: (i) Consultants’ Meeting before the start of the project, (ii) focus on representative tropical acid soils with low fertility, (iii) focus on integrated plant nutrition management, (iv) sustainability and use of locally available natural resources, (v) enhancement of the agronomic effectiveness of natural rock phosphate sources, (vi) close collaboration with other networks (IFDC, CIRAD, IMPHOS, TVA, Latin American Rock Phosphate network), (vii) research, training and analytical services from the IAEA Laboratory, Seibersdorf; CEN Laboratory, Cadarache; IFDC; CIRAD and IMPHOS, (viii) extra-financial resources from the French Government and IMPHOS, and (ix) database for validation of a soil P sub-model for inclusion in the IBSNAT crop models and for providing better P fertilizer recommendations for major food crops in developing countries.

F. Major achievements/outputs, and impact.

- Characterization of the dynamics of soil P (P-32 isotope exchange kinetics) in more than 100 soil samples collected by the participants.

- Data on soil P availability as affected by soil type and P fertilizer source. Information about the performance of routine chemical (extraction) method.

- Data on the agronomic effectiveness of natural and modified rock phosphate products under a variety of agro-ecosystems (P-32 isotope dilution techniques).

- Approaches for enhancing the agronomic effectiveness of natural rock phosphate sources.

- Standardization of methods for evaluating the agronomic effectiveness of P
fertilizers.
- Provision of recommendations on the efficient use of P fertilizers, in particular rock phosphates.
- Publications of the results in local and international journals.
- Promotion for manufacturing more economic and effective P fertilizer sources for acid soils.
- Guidelines for P fertilizer legislation.

G. Overall implementation

The Consultants’ Meeting held in May 1993 delineated the framework of the project. In its initial phase, more than 100 soil samples were collected by the participants to characterise the soil P dynamics parameters using the P-32 exchange kinetics method. The “available” soil P was evaluated by the chemical (extraction) method utilized in each participating country. The specific objective was to assess the performance of the routine chemical method for available P in soils amended with rock phosphate products and water-soluble P fertilisers.

During the second phase most participants conducted greenhouse experiments to evaluate the agronomic effectiveness of local and imported phosphate rocks using P-32 isotope dilution and conventional techniques. Strategies (technological and biological processes) to enhance the agronomic effectiveness of medium to low reactive phosphate rocks were also investigated.

During the final phase of implementation participants conducted field experiments to gather information on the agronomic effectiveness of P fertilisers and phosphate rock-based products under a variety of soil and climatic conditions in well-defined cropping systems. Data collected will be used to validate the P sub-model of the DSSAT family of crop models. Reactive phosphate rocks were provided by IMPHOS.

The standard characterisation of soils and phosphate rocks utilized in the project were made in selected laboratories with the financial support of IMPHOS. The soil analyses were made at the Laboratories of CIRAD, Montpellier, France. The mineralogical studies (mineralogical composition and empirical formulae) of phosphate rocks were carried out in the “Centre des Recherches Petrographiques et Geochemiques”, CNRS, Nancy, France. The physical and chemical characterisation of the phosphate rocks was made in the “Centre d’Etudes et des Recherches des Phosphates Mineraux”, CERPHOS, Casablanca, Morocco.
3. The Fourth and Final Research Co-ordination Meeting

The Fourth and Final Research Co-ordination Meeting of the FAO/IAEA Coordinated Research Project on "The Use of Nuclear and Related Techniques for Evaluating the Agronomic Effectiveness of Phosphate Fertilisers, in particular Rock Phosphates" was held at the IAEA Headquarters in Vienna, Austria, from 16 to 20 November 1998.

The objectives of the meeting were:

a) To review and discuss the results of research carried out during the entire duration of the CRP,

b) To assess the achievements in accordance to the project objectives, including formulation of conclusions and recommendations,

c) To complete the final editing of reports/summaries for publication of the results of the CRP.

The official opening was made by Mr. P.M. Chalk, Head of Soil and Water Management & Crop Nutrition Section of the Joint FAO/IAEA Division, and followed by remarks of Mr. F. Zapata, Scientific Secretary of the CRP.

The programme of the meeting (Annex A) included eleven technical sessions with the presentations of the contractors and agreement holders, two sessions in working groups and one final general session to present and discuss the conclusions and recommendations of the CRP.

The meeting was attended by 26 scientists: 15 contractors, 6 agreement holders, 5 observers. In addition, staff members from Headquarters and the Seibersdorf Laboratory participated. The list of participants is shown in Annex B.

The results presented by the participants of the project are highly relevant to further our knowledge of the chemistry of P in acid soils, soil P testing, P nutrition of crops, and P fertiliser recommendations, with particular emphasis on the utilization of phosphate rocks. Due consideration was also given to environmental issues in the work of the agreement holders. The summaries/abstracts of the presentations are given in Annex C.

The formulation of conclusions and recommendations was made in four working groups, i.e., i) phosphate availability studies including environmental issues, ii) agronomic effectiveness of phosphate fertilisers, iii) field trials and practical recommendations for the application of P fertilisers and, iv) phosphate studies in Eastern Europe. For details please refer to Section 4 of this report. Final reports including summaries were compiled and edited. The manuscripts for the preparation of the final publication of the CRP were also compiled and revised by the authors. Several participants have published their results in local and international journals. A list of publications (work done under contract) is included in Annex D.
During the final session the group leaders presented the conclusions and recommendations for consideration and approval of the participants. The RCM was officially closed by Mr. P.M Chalk. In the afternoon, individual discussions continued with some of the participants.

The quality of the presentations was very good. The many topics addressed in this CRP were grouped into objective-related, methodological and general issues. Some methodological issues and guidelines were discussed for harmonization purposes. The project was evaluated according to the evaluation criteria of the CRPs, i.e. Effectiveness, impact and relevance. All of them have been successfully achieved.

Special thanks are given to all participants for their untiring efforts to achieve the objectives of the CRP according to the Action Plan and to ensure a successful completion. A task lies ahead to disseminate the scientific and technical information generated in the participants’ countries to the benefit of the end-beneficiaries, i.e. the farmers.

4. Conclusions and Recommendations

4.1 P availability studies, including environmental issues

4.1.1 Conclusions on P availability

1. The majority of soils tested for P availability were acid, and P deficient. Neutral soils were tested in Cuba and Romania. Routine chemical tests used to predict P availability by the participants in the CRP are listed in Table 1.

2. There is no single soil P test that can be universally used to estimate available P in soils amended with PR and water-soluble P fertilisers.

3. In most cases, Bray1, Bray2, Oniani, Mehlich I, Mehlich III, over-estimated P availability in PR-amended soils compared to water-soluble P fertilised soils while E1, resin, Olsen, NH4heptaMo, Pi, Exch Ca, 0.5 N Na0H, Colwell provided good estimates of P availability in PR-amended soils. In near neutral Alfisols in Cuba, Bray1 underestimated available P in PR-amended soils compared to water-soluble P fertilised soils. In high P fixing Oxisols in Brazil, Bray1 and Mehlich III provided good estimates of P availability in PR-amended soils.

4. The Pi test works well in determining available P in soils amended with either PR or water-soluble P fertiliser, as evidenced by greenhouse studies (IFDC) and comparisons with E1 (Poland). Background P concentrations in FeCl3 were found to be approximately 5 mg/kg. Sand abrasion and clay adherence to FeOH3 filter strips were observed.

5. Isotopic 32P methods was valuable to assess P dynamics in soil with or without the addition of P fertiliser. Errors were found to be significant in determining E1 values due to very low Cp values that can occur in low available P or high P fixing soils (Australia, Chile, China).

6. Criteria for a “good” chemical extractant method for available P:
UNAVAILABLE P $\longleftrightarrow$ AVAILABLE P (Q) $\longleftrightarrow$ AVAILABLE P (I)

Rapid
Reproducible
Sensitive to changes in Quantity and Intensity
Extracts a similar proportion of bioavailable P (Q/I) across range of crops, soils, management

4.1.2 Recommendations on P availability

1. P must be limiting in any evaluation of plant response to addition of P fertiliser sources.

2. Soil sampling should take into consideration soil management and cropping systems to sample soil amended with PR.

3. A single extractant should be chosen that results in similar proportional extraction of bioavailable P in soil amended with PR and TSP (separate extracts for PR- and water-soluble P-amended soils not advised).

4. Strong acid extractants (pH less than 4 to 5) should be avoided since they solubilize a considerable portion of P from PR that is unavailable to plants.

5. Extractants that employ a sink for P (resin, Pi) or that are alkaline in nature (Olsen, NaOH, modified Olsen) may be useful for predicting P availability in PR- or TSP-amended soils.

6. Each country should evaluate a new soil test for PR- and TSP-amended soils specific for their soil, cropping, and climatic conditions.

7. A new method adopted by a country should be verified with laboratory and field work that evaluates relative yield versus P soil test to determine critical levels for a variety of soil, cropping, and climatic conditions.

8. To utilize huge databases on P soil test levels already gathered on official methods, correlations can be performed between the new and the official method. Correlations should be conducted on soils amended with water-soluble P.

9. Fertiliser application rates for PR can be recommended on the basis of historical data for water-soluble P and AE values for PR determined from greenhouse or field studies.

10. The isotopic P-32 exchange kinetic method should be used as a reference method for soil P availability.

11. Errors in E1 determinations are magnified in labs without chemically pure water and with Si interference with the use of the blue ascorbic acid colorimetric method.
The Malachite green method is recommended to avoid Si interference when analytically determining E1.

12. The data from the isotopic $^{32}$P method employed on soils in the CRP to identify various kinetic pools of soil P should be compiled into one manuscript that highlights the importance of defining the various P pools in relation to resin and Pi methods and P bioavailability.

13. A procedure paper should be developed that explains the isotopic $^{32}$P method to define various kinetic P pools in soil.

14. Organic P bioavailability is not assessed with the various extracts used in this CRP. The importance of organic P bioavailability needs further study, especially in humid acid soils.

15. Calcium released from P rock can be as important as P bioavailability in improving plant growth. This is especially the case in soils of pH less than 5, with low % base saturation.

### 4.2.1 Conclusions on Environmental Issues

1. Cd availability to plants grown on soils amended with PR is lower than in soils amended with fertiliser products formed from PR acidulation. Long term implications on Cd transfer from PR-amended soils to plants have not been addressed.

2. Fluoride accumulation occurred in the top layer of pasture soil from continual PR application in Australia. Fluoride concentrations in herbage were not affected by fertiliser type or soil/site factors.

3. PR-amended soils reduced radioactive Sr-90 and Cs-137 concentrations in plants in the area affected by the Chernobyl accident.

4. Reactive PR-amended soils showed decreased soil acidity and increased exchangeable Ca.

### 4.2.2 Recommendations on Environmental Issues

1. Long-term problems may exist with plant uptake of Cd and other metals in water-soluble and insoluble P fertilisers. Current long-term plots utilized P fertiliser produced from P rock with low Cd that does not address the issue with Cd in fertilisers produced from PR containing higher Cd levels. In addition to being less expensive than water-soluble P, PR may be a better environmental P fertiliser. Further research and use of $^{109}$Cd isotopic methods to study this problem is recommended.

2. Long-term application of water-soluble P and PR may cause F accumulation in the surface layer of pasture soil. With animal ingestion of the soil, F toxicity may occur. Solubility of PR-F in the animal gut needs further study.
3. The mechanism involved in PR reducing radioactive Sr and Cs concentration in plants needs further study.

4. Phosphate rock may be useful in remediating acidic soils with the addition of Ca and increase in the soil pH causing an increase in the Ca/Al ratio in the soil solution surrounding plant roots.
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<th>Country</th>
<th>Soil Type</th>
<th>P rock studied</th>
<th>Standard extract</th>
<th>P availability indices studied</th>
<th>Good (o), Over (+), or Under (-) estimate available PR P compared to TSP</th>
<th>Yield or P uptake vs soil P test</th>
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<td>Mehlich III Bray I Mehlich III</td>
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4.2 Agronomic effectiveness of P Fertilisers

4.2.1 Conclusions

1. The use of P-32 techniques is a very powerful tool to study the P uptake efficiency of P fertilisers.

2. The agronomic effectiveness of PR depends on characteristics of the PR. The most important characteristic is the P solubility of PR which depends on the degree of carbonate substitution for phosphate in the apatite structure.

3. The low reactive PR which is not suitable for direct application can be greatly enhanced in agronomic effectiveness by partial acidulation, or by mixing with a water-soluble P source, or organic materials, as shown by work carried out in Venezuela, China, Cuba, Brazil and Thailand. A commercial PAPR plant has been built in Venezuela.

4. Agronomic effectiveness of PR can be enhanced through biological approaches such as inoculation of mycorrhiza and P-solubilising bacteria as shown by the work done in Spain and Kenya. The effectiveness of PR can also be increased through fermentation of agrowastes, e.g., sugar beet. The effectiveness can be further increased with mycorrhiza inoculation as shown by work done in Spain.

5. The relative agronomic effectiveness of PR and modified PR products with respect to the water-soluble P source depends on the rate of P applied and crop species, e.g., crops of long growth cycle, nitrogen fixing crops, crops with roots that can release/exudate organic acids (e.g., canola, lupin).

6. The utilization of PR is most effective on soils with the following properties:
   a. Low pH
   b. Low available soil P
   c. High CEC and low exchangeable Ca
   d. High organic matter content

4.2.2 Recommendations

1. Future research should continue to use P-32 techniques to study the agronomic efficiency of P fertilisers.

2. It is recommended that PR-based products should specify the following information:
   a. Origin of PR (location of PR mine, country)
   b. Chemical composition including free carbonate content
   c. P solubility of PR as measured by 2% citric acid or 2% formic acid
   d. Particle size distribution of PR

3. Research is needed to study the agronomic effectiveness of modified PR products such as granulated PAPR or mixture of PR with a water-soluble P source. This approach not only increases the effectiveness of PR, but also eliminates the undesirable dustiness of PR powder.
4. Research is needed to investigate the relationship between PR solubility or particle size with agronomic effectiveness of PR and modified PR products (PAPR and granulated PR with a water-soluble P source). This information will be used for standardization and recommendation of PR solubility test and particle size analysis.

5. Research is needed to study the micronutrient values of PR and the potential uptake of heavy metals by plants from PR. This information is relevant to the potential micronutrient value and environmental impact of PR use.

6. Research is needed to study the processes of the enhancement of PR effectiveness by organic amendments through composting and biological (mycorrhiza and P-solubilising bacteria) approaches.

7. In order to maximise PR effectiveness, it is recommended that PR application be broadcast and incorporated into the soil. Research is also required to study the best placement, timing and cropping system of PR for flooded rice and timing for upland crops.

8. Further studies are needed to standardize the evaluation of the relative agronomic effectiveness of PR with respect to a water-soluble P source:
   a. At multiple P rates, or
   b. At high and low P rates, or
   c. At the officially recommended P rate

9. Research is recommended to study the proper management of liming in relation to the effectiveness of PR. This information is relevant to the management of Al toxicity and PR effectiveness.

10. Research should be emphasised on screening and breeding of crop genotypes and agroforestry species that are efficient PR utilisers.

**4.3 Practical Recommendations for Applications of P Fertilisers**

**4.3.1 Conclusions**

1. Fourteen reports presented results of field experiments during the final RCM; three other participants reported on field experiments under way. Few presented data from “on-farm” trials.

2. Different PR-based products were evaluated by the participants: PR, PAPR, PR + TSP, PR + SSP. The effect of mycorrhizal fungi and rhizobacteria on PR effectiveness were studied in two experiments, one of them included the effect of organic amendments at rates varying from 22 to 400 kg P2O5/ha.

3. Field experiments were carried out on a wide variety of soil types, but in most cases with one common property: low pH (acid soils) with P nutrient limitations for crop growth. Some neutral to alkaline soils were also included.
4. Field experiments were carried out under a wide variety of climatic conditions; from tropical to temperate, and in all cases under rainfed conditions. The application of P fertilisers including PR gave a good response.

5. Field experiments were carried out with a wide variety of crops to measure P fertiliser efficiency: maize (Venezuela, Hungary), sorghum (Venezuela), sugar cane (Cuba), soybean-maize rotation (Thailand), lowland rice (Brazil, Indonesia), soybean (Brazil), eucalyptus (Brazil), winter wheat (Hungary), wheat-maize-soybean rotation (Romania), rice-soybean-mungbean rotation (Indonesia), buckwheat (China), alfalfa-corn intercrop (Spain), pine (USA), pasture (Australia), barley (Russia, Lithuania, Hungary), peas (Hungary), beet (Lithuania), lupin (Chile) and common bean (Cuba).

6. Several evaluation criteria were utilized. The most common ones were dry matter and agronomic (grain) yield, P uptake and isotopic-derived P efficiency indexes (Pdff, Utilization Coefficient, Substitution Ratio). Other criteria included: parameters to reclaim acidic, denuded land, the uptake of Cd and F and the uptake of Cs-137 and Sr-90 in Chernobyl-contaminated soils.

7. The field experiments showed the efficiency of P-32 isotopic techniques to determine accurately the actual P uptake from various sources by plants.

8. A set of data from these field experiments has been collected. A data base will be created and used to validate the P sub-model for integrating plant-soil and climatic conditions and for extrapolating the results.

9. Most participants have produced several scientific publications and others are on the way to be published.

### 4.3.2 Recommendations

1. Some participants still have experiments under way and results will be available within one year. Actions must be taken to ensure that this information is presented to the IAEA. The Joint FAO/IAEA Division should continue to monitor these activities in order to collect that information. In this context, it will be useful to organize a workshop within the network in order to integrate the results.

2. It is required to conduct medium to long-term “on-farm” trials to validate the research results and extrapolate information to other agro-ecological conditions. It will be useful to organize a follow-up programme to demonstrate the impact and benefits of the results obtained with the support of national and international organizations.

3. All reports dealt with the application of sources of inorganic P. Future research should consider studies on the incorporation of organic materials in strongly weathered acid soils of the tropics and sub-tropics and their role as a source of P and/or on the of P fertiliser efficiency. This will contribute to the sustainability of the system.

4. It is necessary to conduct further research to exploit plant genotypic differences in both
aluminium (acidity) tolerance and P use efficiency. Also required are, microbiological studies with mycorrhiza, rhizobacteria and other micro-organisms to further assess their value as a complementary tool to increase the P efficiency use from PR and other P sources.

5. It is important to perform an economic analysis of the results to show not only agronomic but also economic efficiency data. This information is essential for the industry and policy makers to define P fertilisers policies. In this context, a co-ordinated approach between researchers, policy makers and manufacturers is required.

6. It is necessary to complete the collection of the minimum data set and submit them to the IAEA, so that the P sub-model can be validated under a variety of conditions of the experiments.

7. In order to facilitate the application of the results and obtain the expected impact, it is necessary to organize activities for training of the decision makers and extension personnel through workshops and for their dissemination to the farmers through the publication of leaflets and extension bulletins.

8. The policies for soil fertility re-capitalisation recommended for different areas of the world, would include the massive application of phosphate rock as an initial investment, in order to make their different capitalization projects viable. A proper characterisation of soils, plants, P sources and climatic conditions is necessary to achieve good results.

4.4 Phosphate Studies in Eastern Europe

4.4.1 Introduction

During the period 1970-1990 in all participating countries the application rates of phosphorus in mineral and organic fertilisers were rather high and surpassed the P uptake of the crops. This practice resulted in a steadily improvement of the soil P fertility status and by the end of 80’s soils showing high to very high phosphorus contents covered 40 - 80 % of the agricultural land.

Since the beginning of the 90’s, the situation changed dramatically with changing economic conditions. As a result of the lifting of the fertiliser subsidy and the narrowing of the cost/price ratio for fertilisers and agricultural products, the consumption of mineral fertilisers, in particular phosphatic sources, has declined several times. During the past few years P fertilisers were applied in the range of a few kilograms to less than 20 kg P2O5/ha, and the soil P status started to deteriorate slowly. This situation has been reflected directly in the results of soil monitoring programmes and indirectly in the crop yield decreases.

At present, with regard to the soil P status, three situations can be found:

1. Soils with sufficient available P, according to the routinely used soil testing methods. In this case, the main problem lies in maintaining the already achieved P fertility level.
2. Soils showing inherently low phosphorus content and/or soils where P availability is seriously limited by constraints such as acidity and heavy texture (degradation of soil fertility).

3. Soils contaminated with toxic substances, radionuclides from the Chernobyl accident, heavy metals and some organic contaminants.

4.4.2 Work programme

The recruitment of 5 new contractors plus one from Romania (thanks to the financial support of the French Government) and the elaboration of the work programme was made in 1996.

Most studies which started in 1997 focused on the three situations mentioned above with the following objectives:

1. In the soils belonging to the first category only the maintenance of the P status is needed through a rational and efficient use of water-soluble P fertilisers (SSP, TSP).

2. In the soils showing inherently low phosphorus content and/or soils where the P availability is seriously limited by some constraint, other sources of phosphorus like phosphate rocks (PR) can be also taken into consideration.

3. One countermeasure for use in contaminated soils may be the application of P fertilisers, in particular rock phosphates from local deposits.

4. In all cases, there is a need for updating methods for determination of soil and fertiliser-derived phosphorus availability using nuclear and related techniques. Ultimately, the updated methods should contribute to a better utilisation of phosphorus fertilisers and to include them into routine soil testing for fertiliser recommendation systems.

In this context, it is necessary to mention that some participating countries had very little experience in both the application of rock phosphate and the utilization of the P-32 isotopic exchange kinetic technique. The project contributed substantially to the exchange of information and collaboration with leading laboratories from the countries participating in the CRP from the very beginning i.e. 1993.

4.4.3 Results obtained

In all 5 countries a set of representative soil samples was collected, and analysed by the local routine methods. Thereafter, they were sent to CIRAD-CA, Montpellier, France for standard soil characterisation and to CEA, CEN - Cadarache, France for P-32 isotopic kinetic exchange studies. In this connection, the support and personal contributions of Messrs. Denis Montagne and Jean-Claude Fardeau are highly appreciated.

The soil samples were amended with soluble-P fertilisers and PR, and used in
laboratory incubation experiments. During the incubation studies, the fate and behaviour of the applied phosphorus was followed with the locally-available methods, and in the case of Poland, with isotopic exchange kinetics as well due to the support of the FAO/IAEA Seibersdorf laboratory.

In most countries, greenhouse experiments were carried out with different soils crops and fertiliser treatments to evaluate the efficiency of different P forms. No significant differences in the efficiency of superphosphate and the reactive, finely-ground PR were found in acid soils.

In some countries, field experiments were either established or continued (long-term experiments) with the aim of comparing the effects of different sources of phosphorus in soils and plants. Similar results to the greenhouse experiments were obtained.

Special greenhouse and field experiments were carried out in Belarus and the Russian Federation to investigate the effect of phosphorus fertiliser application as a countermeasure for minimising the transfer of radionuclides Cs and Sr from contaminated soils to the plants. It was found that the phosphorus fertilisers reduced by 1.2 - 1.3 times the Cs-137 concentration and up to 2.0 times the Sr-90 concentration in plants.

4.4.4 Conclusions
All countries completed their research programmes to the extent indicated in the projects, fulfilling the terms of the contracts. The results contributed substantially to enhance the state of knowledge concerning P fertiliser utilisation and updating the methods of soil analysis for plant available phosphorus.

The two years’ research period was insufficient for fully developing an improved P fertiliser recommendation system and for transferring results to agricultural practices. Therefore, further co-ordinated activities supported by external resources seem to be valuable and necessary.
Annex A

Programme
MONDAY, 16 NOVEMBER

09:15-09:30  OFFICIAL OPENING
             P. M. Chalk, Head
             Soil and Water Management & Crop Nutrition Section.

09:30:10:00  Remarks by Scientific Secretary

10:00-10:30  Coffee break

SESSION I  Chairperson: P.M. Chalk

10:30-11:15  E. Casanova (VEN)

11:15-12:00  J. Herrera (CUB)

12:00-14:00  Lunch Break

SESSION II  Chairperson: G. Keerthisinghe

14:00-14:45  K. Mwendwa (KEN)

14:45-15:30  J. Mahisarakul (THA)

15:30-16:00  Coffee Break

SESSION III  Chairperson: F. Sikora

16:00-16:45  T. Muraoka (BRA)

16:45-17:30  I. Pino (CHI)

TUESDAY, 17 November

SESSION IV  Chairperson: S.H. Chien

08:30-09:15  Z. Borlan (ROM)

09:15-10:00  Z. Rahman (MAL)

10:00-10:30  Coffee Break
SESSION V  
Chairperson: D. Montange
10:30-11:15  E. Sisworo (INS)
11:15-12:00  Li Ming Xiong (CPR)
12:00-14:00  Lunch Break

SESSION VI  
Chairperson: D. Stevens
14:00-14:45  J. M. Barea (SPA)
14:45-15:30  S. H. Chien (USA)
15:30-16:00  Coffee Break

SESSION VII  
Chairperson: J. M. Barea
16:00-16:30  Truong Binh (FRA)
16:30-17:00  R. N. Roy (FAO)
17:00-17:30  A. Benjelloun (IMPHOS)

WEDNESDAY, 18 November

SESSION VIII  
Chairperson: R.N. Roy
08:30-09:15  F. Sikora (USA)
09:15-10:00  D. Stevens (AUL)
10:00-10:30  Coffee Break

SESSION IX  
Chairperson: P. Moutonnet
10:30-11:15  J.C. Fardeau (FRA)  
             M. Aigner (IAEA)
11:15-12:00  D. Montange (FRA)
12:00-14:00  Lunch Break
SESSION X  Chairperson: Truong Binh
14:00-14:30  R. Alexakhin (FIS)
14:30-15:00  I. Bogdevitch (BYE)
15:00-15:30  Coffee Break
SESSION XI  Chairperson: J.C. Fardeau
15:30-16:00  M. Fotyma (POL)
16:00-16:30  T. Nemeth (HUN)
16:30-17:00  V. Sidlauskas (LIT)

THURSDAY, 19 November
SESSION XII  WORKING GROUPS
09:00-12:30  Formulation of Conclusions and Recommendations.

WORKING GROUP A: Phosphate availability studies (including environmental issues).
   Sikora, Fardeau, Montange, Muraoka, Pino, Stevens, Xiong.

WORKING GROUP B: Agronomic effectiveness of phosphatic fertilizers.
   Chien, Barea, Binh, Mwendwa, Mahisarakul, Sisworo, Zaharah.

WORKING GROUP C: Field trials. Practical recommendations for application of
   P fertilisers.
   Casanova, Benjelloun, Borlan, Herrera, Roy.

WORKING GROUP D: Phosphate studies in Eastern Europe.
   Fotyma, Alexakhin, Bogdevitch, Nemeth, Sidlauskas.

12:30-14:00  Lunch Break

SESSION XIII  WORKING GROUPS (Cont.)
14:00-18:00  Preparation of reports by Working Groups
   Review/Editing of summaries, Final Reports and Manuscripts for publication.
   Individual meetings with Scientific Secretary.

FRIDAY, 20 NOVEMBER
<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<tr>
<td>09:00-10:00</td>
<td>Conclusions and Recommendations</td>
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<td>Presentation and general discussion</td>
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<td>10:00-10:30</td>
<td>Coffee Break</td>
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<tr>
<td>10:30-11:30</td>
<td>Conclusions and Recommendations (Cont.)</td>
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<td>11:30-12:00</td>
<td>CLOSING</td>
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<td>12:00-14:00</td>
<td>Lunch Break</td>
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ANNEX B

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Annex C

Summaries of

Work Done During the CRP
Studies on the effectiveness of rock phosphates as agricultural countermeasure in soils contaminated by radionuclides

Rudolf Alexakhin

A series of experiments on the agronomic assessment of locally available rock phosphates (RP) and their possible use to decrease $^{137}$Cs and $^{90}$Sr accumulation in field-grown crops were carried out over a two year period. The following experiments were carried out: 1) a greenhouse experiment to assess the agronomic effectiveness of the Polpino rock phosphate deposit in 1997 and its follow-up in 1998 to estimate after-effect or residual effects of applied RP; 2) a laboratory study to evaluate the dynamics of changes in the mineral forms of soil P one year after PR application; 3) a field experiment on the agronomic and radio-ecological assessment of local RP on the territory of the Bryansk region.

Standard methods for soil and plant analysis and evaluation of chemical status of soil P were employed. The contents of $^{137}$Cs and $^{90}$Sr in soil and plant samples were measured by radiochemical and $\gamma$- spectrometric techniques.

In the 1997 greenhouse experiment the relative availability of P PR from the Polpino deposit was compared to superphosphate applied at three increasing rates, i.e., 21.8, 43.6 and 87.2 mg P/kg soil in a soddy-podzolic acid soil with barley as test crop. Grain yield increased by 17.7, 44.3 and 57.5% over the control at the P increasing rates respectively. The total P uptake also increased but the P taken from the fertiliser decreased with the increasing P rates. These declines were less pronounced for the local RP. The P recovery by the plants from the local RP was on the average 2.1 times less than that from SP. The application of the local RP at the intermediate and high rates of P resulted in a 1.3 fold decrease in $^{137}$Cs accumulation in grain and straw of barley. At the low P rate the differences in $^{137}$Cs accumulation in grain and straw compared to the control were insignificant.

In the 1998 greenhouse experiment, data were obtained on the residual effects of previously applied P fertilisers on the yield of barley. The agronomic effectiveness of local RP in the second year after their application to soil was found to be comparable with that of previously applied superphosphate (SP). In year 2 after the application the coefficients of P use by plants from SP and RP had close values and varied between 5.6 and 7.6%.

The results of the field experiment showed that the largest increase, by 62.4 and 90.1 g/m², compared to the control, was observed in SP treatments at doses of 40 and 80 kg P/ha, respectively. The application of RP resulted in the grain increase of 29.3 and 58.7 g/m². The calculations based on the conventional method have demonstrated that plants used 1.7-1.9 times less P from RP than from SP at equivalent rates.

The studies of the dynamics of the mineral forms of phosphates following the application of local RP have revealed that one year after their contact with soil the number of sparingly soluble mineral forms of P from local RP reduced from 59.2% to 24.0%. In this case significantly the number of the P mineral forms bonded to Fe and Al increased.

In both greenhouse and field experiments, the effect of RP on $^{137}$Cs and $^{90}$Sr accumulation in the barley yield were evaluated. In year 2 after RP application of the greenhouse experiment the decrease in the $^{137}$Cs mobility was approximately the same as in the first year. It was found in the field experiment that in RP and SP treatments at 40 kg/ha, the differences in $^{137}$Cs accumulation in grain and straw are insignificant compared to the control. An
increase in the rate of P up to 80 kg/ha caused a 1.2-1.3 fold decrease in $^{137}$Cs accumulation in grain, and the application of RP was more effective than SP. The results from the field experiment have also shown that P fertilisers exert greater effect on the biological mobility of $^{90}$Sr than on that of $^{137}$Cs. RP show higher reducing effect on $^{90}$Sr accumulation in grain and straw of plants compared to SP. The maximum decrease in accumulation in grain and straw, factors of up to 1.8 and 1.9 compared to the control, was reported for the RP treatment at 80 kg/ha.

The use of mycorrhizas and phosphate solubilising micro-organisms to improve the agronomic effectiveness of natural sources of rock phosphate. Scientific background and scope of project

José-Miguel Barea

The effects of some microbiologically-mediated processes on improving the agronomic efficiency of rock phosphate sources are currently recognised. Recent interest on the topic is based on the demonstrated activities of mycorrhizal fungi, particularly those forming the called arbuscular mycorrhiza (AM). In such symbiotic association the fungus (AMF) colonise biotrophically the root system of agronomically important crop species to establish a universal mycorrhizal system. The symbiotic fungi also develop an external mycelium which colonise extensively the soil surrounding the roots. Thereby the mycorrhizal symbiosis, by linking the biotic and geochemical portions of the ecosystem, can contribute to nutrient capture and supply to the plants. The AM fungi can also improve soil structure and stimulate other beneficial members of soil microbiota. In addition, some phosphate-solubilising bacteria (PSB), able to solubilize rock phosphate in vitro, have been characterised as rhizobacteria, because of their “aggressiveness” in colonising the root region of crop plants where they can change phosphate bioavailability. Some rhizobacteria can even improve mycorrhiza formation. Manipulating such micro-organisms the plant can be furnished with an active mycorrhizosphere, which could be specifically tailored to try to improve the use of less available P sources, like rock phosphates.

The use of isotopic ($^{32}$P) approaches may allow to determine the extent of a possible transformation of unavailable soil P into bioavailable P by the metabolic activities of soil micro-organisms.

Research objectives
1. To develop laboratory/greenhouse experiments to select appropriate mycorrhizal fungi/bacteria combinations able to improve the use of several sources of rock phosphate.
2. To test in the field the effect of these micro-biologically-mediated processes in improving the plant to use rock phosphate under Mediterranean climatic conditions.

Experimental Methods
Concerning the Research Objective # 1, experiments were carried out using techniques related to:

a. Isolation, selection and tagging of plant growth-promoting rhizobacteria (PGPR), efficient solubilizers of rock phosphate.
b. Isolation and selection of efficient mycorrhizal fungi (AMF).
c. Selection of AMF/PGPR combinations for "functional compatibility" with the host plants (genotype selectivity).
d. Idem as in -c- for their ability to improve the establishment of each other to develop an active mycorrhizosphere.
e. Development of appropriate methodologies to apply $^{32}$P (and $^{15}$N for legume crops) to evaluate the efficiency of the biological interactions to improve the use of rock phosphates by the plants. The isotope dilution techniques have been used in micro and mesocosms experiments.

Research Objective # 2:

a. Applications for developing sustainable soil-plant systems.
b. Use $^{32}$P-aided techniques (according to the guidelines of the Joint FAO/IAEA Programme) to evaluate the impact of these microbial processes in agriculture. These activities were carried out under field conditions.

Results obtained

1. We have demonstrated an improvement of arbuscular mycorrhizal development by inoculation with phosphate-solubilizing rhizobacteria and its beneficial effect on rock phosphate bioavailability ($^{32}$P) and nutrient cycling, leading to a sustainable nutrient supply.
2. By using isotopic ($^{32}$P and $^{15}$N) dilution techniques we have found positive interactive effects of *Rhizobium*, mycorrhizal fungi, phosphate-solubilizing rhizobacteria and rock phosphate to improve P and N acquisition by legume crops.
3. We have proposed microcosm bioassays to ascertain whether the effect of mycorrhizal fungi and phosphate-solubilizing rhizobacteria are able to improve the effectiveness of rock phosphate sources in neutral, low Ca, soil, by using $^{32}$P isotopic dilution approaches.
4. We have demonstrated the utility of using $^{32}$P dilution techniques to evaluate the effect of mycorrhizal inoculation on plant uptake of P released from the resulting products of fermentation mixtures including agrowastes, *Aspergillus* and rock phosphate.
5. We have demonstrated an improvement of the agronomic effectiveness of rock phosphate by applying the interaction between mycorrhizal fungi and phosphate solubilizing rhizobacteria with organic matter amendments in intercrop systems under field conditions.

Conclusions drawn

1. The use of isotopic ($^{32}$P) dilution approaches allowed us to demonstrate that the interactions between mycorrhiza and phosphate-solubilizing rhizobacteria improved plant P acquisition from rock phosphate materials in a neutral, low-C agricultural soil.
2. The inoculated rhizobacteria improved mycorrhizal establishment and, in turn, the mycorrhizal status favoured rhizobacteria establishment in plant rhizosphere.
3. The interaction between mycorrhizal fungi and phosphate-solubilizing rhizobacteria contributed to the biogeochemical cycling of nutrients, particularly with regard to the use of RP, by more than just providing a greater surface area scavenging mineral nutrients that may be relatively immobile in soil or in short supply (like phosphate). The
established mycorrhizosphere system seems to be also able to retain nutrients within the biomass thereby contributing to a sustainable nutrient supply to plants.

**Rock phosphate standard characterisation**

**Truong Binh**

28 phosphates utilized in this network were collected from 15 countries, representing a large variability of origin, treatment, and transformations. Mineralogical composition (mineralogy, crystallography), physical (granulometric distribution, specific surface and porous volume) and chemical (total element composition, P solubility in conventional reagents) analyses were carried out in well established laboratories using standard methodologies. This standard characterisation was made within the frame of a Co-operation Agreement between the Joint FAO/IAEA Programme and the World Phosphate Institute.

The results confirmed the variability of the samples but also allowed to group them according to different criteria such as minerals content, total element composition, P solubility and reactivity. Further studies should be pursued for their validation through their correlation with the agronomic data obtained in controlled and field conditions.

**Comparative Evaluation of the Effect of Rock Phosphate and Mono-ammonium Phosphate on Plant P-nutrition in Sod-podzolic and Peat Soils**

**Iossif Bogdevitch**

The direct application of finely powdered rock phosphate (RP) imported from Russia has been suggested as an alternative to the almost twice more expensive water-soluble mono-ammonium phosphate (MAP) on acid soils. The direct application of RP potentially might be effective on acid (moderately limed) sod-podzolic and peat soils, which occupy about 30% of agricultural land of Belarus.

Two pot experiments were conducted in 1997 and 1998 (1) to make a comparative evaluation of availability of phosphorus from RP and MAP for growing crops and (2) to study effect of P fertilisers on the reduction of the root uptake of radionuclide $^{137}$Cs in the contaminated soils. Lupin was grown on sod-podzolic silty clay loam soil with pH H2O 6.2 and medium level of available P and ryegrass on peat soil with pH 4.9 and low level of the native soil P fertility, using the $^{32}$P isotope dilution technique.

Application of RP and MAP at rate 40 mg P/kg soil contributed similarly to the P nutrition of lupin plants. The Pdff values, i.e., the fractions of P in the plants derived from the applied RP and MAP were 7.4 and 8.4%, respectively and P fertiliser recovery values - about 1% for both fertilisers. The application of RP and MAP on peat soil had different effects on P nutrition for rye grass plants. The Pdff values were 14.9% for RP and 22.1% for MAP. It may be concluded that for most of the crops on sod-podzolic soils it is preferable to apply MAP water-soluble P forms. However, for the plants with a high root ability to utilise P, such
lupin, on acid sod-podzolic silty clay soils (pH H20<6.0) RP may be used for direct application as well as water-soluble P fertilisers. In common, for peat soils application of water-soluble P fertilisers is also preferable. Taking into consideration the difference in cost of the fertilisers, RP application to acid peat soil (pH H20<5.0) may be reasonable for substantial improvement of grassland in the radionuclide contaminated area.

The results of second pot experiment suggest that direct application of RP may be more effective than the use of water-soluble P fertilisers in reducing the plant uptake of 137Cs on the acid sod-podzolic and peat soils. A significant reduction of the root uptake of 137Cs by lupin on RP-treatment (-16%) and MAP (-8%) was found in comparison with that of the control treatment. The activity of rye grass plants on peat soil decreased by 27% after application of RP, but only 7% after MAP application. These data are very important, because the tested soils are widely spread in the area by the Chernobyl accident. It is necessary to continue the comparative evaluation of RP and MAP effectiveness in field trials for developing economically sound practical recommendations. Direct application of RP may be one of the effective countermeasures for decrease of 137Cs transfer from the contaminated acid soils to the crop production.

Soil conditions promoting and restraining agrochemical effectiveness of water-insoluble phosphate sources, in particular, phosphate rock

Zenoviù Borlan

Aspects of phosphate rock (PR) use instead of water soluble phosphorus sources were investigated. The studies were conducted using both 32P radioisotope dilution technique and the (non-isotope) difference method. Maize for green fodder (Zea mays L.) and ryegrass (Lolium multiflorum Lam.) were grown in Mitscherlich type pots of 7 Kg dry soil and in small pots of 1.25 Kg dry soil capacity, respectively, on several base-unsaturated Hapludoll and Hapludalf soils. Soil aptitude to be dressed with phosphate rocks (PR) was judged based on experimental data considering soil adsorbed acidity (Ah), humus content (H2), cation exchange capacity (T), sum of exchangeable bases (SEB) and mobile (easily soluble) phosphate content (PAL) in the soil, combined in a rock phosphate use opportunity index of the soil (PRUOIS):

\[ PRUOIS = \frac{A_h \cdot H^2 \cdot T \cdot 100}{SEB \cdot 10^{0.0245\cdot PAL}} \]

Rock phosphate suitability for direct use was evaluated by means of rate of PR-P dissolution (PRPRS) in a 0.6% ammonium heptamolybdate in 0.01M calcium chloride solution (ppm P) and its carbonate content (%CaCO3) in PR, both combined in a phosphate rock suitability index for direct use (PRSIDU):

\[ PRSIDU[ppmP/min] = PRPRS \cdot (1 - 0.03 \cdot CaCO_3) \]

Water-insoluble PR sources studied were: fluor apatite from Kola-Russia; Morocco;
Neither PRUOIS nor PRSIDU taken apart could explain satisfactorily the variance of PR efficiency as P source as determined both by $^{32}$P isotope dilution and difference method, while synthetic index obtained by multiplicative combination of these: PRUOIS $\times$ PRSIDU did correlate highly significantly with indices of agronomical efficiency of PR, assuring their determination of at least 80%.

Furthermore, the use of the PRSIDU $\times$ PRUOIS synthetic index to estimate the rate of PR required for partial (or complete) replacement of soluble P fertiliser sources on low P base unsaturated soils is proposed. Such a proposal is due to mutual compensation between PR and soil chemical properties in PR-P mobilisation for plants, implied by above mentioned synthetic index.

The report describes also that by means of $^{32}$P isotope dilution methodology, it was possible to enhance productive use of PR-P in plants by applying together PR with water soluble P sources as well as by foliar application of neutral aminoacid and ureide-containing diluted solutions. By means of this methodology it is demonstrated that the positive influence of such practices upon PR-P reactivity in soils and P absorption by plants is statistically significant.

A procedure of extracting soil mobile P with a 0.6% solution of ammonium molybdate (hepta) in 0.01M CaCl$_2$ at a pH of 4.3 was found to give the best picture of available P in PR-dressed soils (as compared with Al, NaHCO$_3$ and NH$_4$F-HCl-Bray methods). When used at the end of the ryegrass pot experiments (after about 150 days of PR interaction with the soils) all tested methods of extracting easily soluble P gave similar results for assessing the suitability of PR for direct use.

**The use of nuclear and related techniques for evaluating the agronomic effectiveness of phosphate fertilisers, in particular rock phosphate, in Venezuela**

Eduardo Casanova, A. M. Salas y M. Toro

In Venezuela, 70 % of the soils are acid with low natural fertility being phosphorus (P) the most limiting element together with nitrogen and potassium. The efficiency of the applied P fertilisers is low, therefore, greenhouse and field experiments were conducted to evaluate the efficiency of natural and modified rock phosphate using conventional and isotopic techniques. In order to know the dynamics in the soil P availability parameters, a laboratory incubation experiment was established with the application of different phosphate fertilisers at a constant rate of 100 mg P/kg in ten acid soils of important agricultural areas of Venezuela. Two greenhouse experiments were carried out to quantify the effect of P fixation on soil P availability and the response of an index crop (*Agrostis sp*). Field experiments were conducted in acid soil from El Pao, Cojedes state, to evaluate the effects of different phosphate fertilisers in maize measuring dry matter production during the growing season, P accumulated in plant, efficient parameters using isotopic techniques and yield as well as the presence of P-solubilizing micro-organisms. Finally, commercial plots were established with the application of soluble P fertilisers and natural and modified rock phosphate to validate the results obtained in the field experiments.
The laboratory results showed a high variability in the P fixing capacity of the soils \((r_{1/R_0}= 0.02-0.76)\) in soils with similar level of available P and this was confirmed by the available P extracted by Bray I with a range of 10 to 88 % of P removed by the Bray solution. The incubation studies showed that the effectiveness of the P sources related to their reactivity and the soil P fixing properties. Increasing the soil P fixing capacity caused a significant reduction in the E value, independently of the source used. A high positive and significantly correlation between the P extracted by Bray and the E value \((r = 0.95)\) obtained from the different treatments, showed the affinity of the extractant for some forms of available P in soils where rock phosphate was applied.

In the greenhouse experiment, the crop response was related to the P fixing properties of the soil, the initial availability and the solubility of the P source used. The P derived from the fertiliser \((\%P_{dff})\) and the Utilization Coefficient \((UC)\) decreased significantly with the increase of P fixing capacity indicating a lower P availability to the crop.

P solubilizing micro-organisms (fungus and bacteria) from field-growing corn and beans were isolated and quantified to inoculate them in greenhouse and field experiments and evaluate their effectiveness in solubilizing natural and modified rock phosphate. There was a trend to obtain higher total microflora values in the corn rhizosphere due to the roots exudates. Two solubilizing fungus were identified: *Aspergillus terreus* and *Aspergillus niger*. In the semi-commercial plot highly significant differences were found between the rock phosphate partially acidulated and the natural rock phosphate and the check plot in dry matter production, P accumulation in plant and grain yield. The efficiency parameters which were evaluated in microplots with \(^{32}\)P-TSP at 60 days of plant growing, confirmed the results obtained in the semi-commercial plots. The values of P derived from the fertiliser in the plant were 46 % of the partially acidulated rock phosphate (PAR) and 14 % of the natural Rock phosphate (RP) with a utilization coefficient of P by the plant of 34.2 and 8.8 % for both treatments, respectively. The Substitution Relation parameter showed that it is required just 0.8 kg of P of PAR and 3.1 kg of PR to produce the same yield than 1 kg of TSP. These results were validated in commercial 5 ha demonstrative experiments in Valle la Pascua and El Tigre soils with corn and sorghum.

The Use of Nuclear and Related Techniques for Evaluating the Agronomic Effectiveness of Phosphate Fertilizers, in Particular, Rock

S. H. Chien

Use of conventional, water-soluble phosphate (P) fertilizers by the resource-poor farmers in developing countries has been limited by its high cost. Direct application of finely ground indigenous phosphate rock (PR) to tropical and subtropical acid soils for crop production is an attractive option for the farmers because of low capital investment and production costs. The main objective of this project was to use nuclear and related techniques to assess the agronomic effectiveness of PRs, and where necessary, means of enhancing their effectiveness. The issue of potential cadmium (Cd) which is a toxic heavy metal to humans associated with the use of P fertilizers was also investigated.

Experimental Methods
During the 5-year period of this project, IFDC conducted three greenhouse experiments:

1. A $^{32}$P isotope dilution technique was used to study P availability of a medium-reactive PR as enhanced by water-soluble P (TSP) at various P rates to maize and cowpea grown on an acid soil (pH 4.8). In this experiment, both soil and water-soluble P were tagged with $^{32}$P and the activity of $^{32}$P in the plant digests was measured after 42-45 days of plant growth.

2. A modified iron oxide-impregnated paper strip (Pi test) was developed by replacing $0.01 \text{ M CaCl}_2$ with $0.02 \text{ M KCl}$. Two acid soils were treated with a highly reactive PR or TSP at various P rates. Maize was grown for 5 weeks and soil samples were taken for Pi and Bray I extractions. P uptake by maize was measured and correlated to soil extractable P.

3. Two high Cd-containing PRs, North Carolina (NC) PR and Togo PR, were acidulated at 50% and 100% levels with H$_2$SO$_4$. Two acid soils were treated with unacidulated PR, partially acidulated PR (PAPR), and fully acidulated P (SSP) as sources of Cd at various Cd rates. All the treatments received a high P rate (200 mg P/kg) as KH$_2$PO$_4$ to equalize P response. Upland rice was grown to maturity and Cd uptake by rice was measured in root, straw, and grain.

Results Obtained

In the first experiment, the effectiveness of P sources in terms of increasing dry-matter yield and P uptake followed the order of TSP $\geq$ (PR + TSP) > PR for maize and TSP = (TSP + PR) > PR for cowpea. P uptake from PR in the presence of TSP was higher than P uptake from PR applied alone. With respect to P uptake form PR applied alone, the corresponding relative increase in P uptake from PR due to TSP influence was 165% for maize and 72% for cowpea. In the second experiment, both Bray I and the Pi test with CaCl$_2$ underestimated available P from PR with respect to TSP. Available P estimated by the Pi test with KCl was more closely related to P uptake with both PR and TSP. More P was extracted from PR by the Pi test with KCl than with CaCl$_2$, whereas no effect was observed for TSP. In the third experiment, Cd uptake by rice grain followed the order of NC-SSP > NC-PR and Togo-SSP > Togo PAPR > Togo PR. The results also showed that most of the Cd uptake was retained in rice root and straw. Total uptake of Cd, Ca, and P by the rice plant was higher from NC-PR than from Togo-PR. Cd concentration in rice grain showed no significant difference between NC-PR and Togo-PR, whereas Cd concentrations in root and straw were higher with NC-PR than that with Togo-PR.

Conclusions

1. Use of the $^{32}$P isotope dilution technique is a powerful tool to study the agronomic efficiency of PR as enhanced by water-soluble P.

2. The modified iron oxide-impregnated paper strip (Pi test) by replacing $0.02 \text{ M CaCl}_2$ with $0.02 \text{ M KCl}$ is an effective soil P test for both PR and water-soluble P.

3. Acidulation of Cd-containing PR clearly increases Cd uptake by crops. If unacidulated PR or partially acidulated PR are agronomically as effective as fully acidulated PR, these water-insoluble or partially water-soluble P sources may also contribute less to
Cd uptake by crops than the use of water-soluble P sources.
Assessment of available soil P and effectiveness of P fertiliser by two different methods. 
The advantage of using the isotopic exchange kinetic method.

Jean-Claude Fardeau and Martina Aigner

Assessment of available soil P. Native available soil P was assessed through the isotopic exchange kinetic method (IEK) and the Pi paper method in 250 topsoil samples taken from both tropical climates and continental temperate climatic conditions. The IEK method provides a full characterisation of the available soil P determining four independent factors in a single experiment. The intensity factor is quantified by the measurement of the chemical potential $C_P$ of phosphate ions in the soil solution, the quantity factor is estimated by the quantity of phosphate ions being instantaneously isotopically exchangeable at 1 minute ($E_1$). Two capacity factors - one “immediate” and another “delayed” are simultaneously determined. It was shown that the capacity factors can explain more soil properties with respect to phosphate ion availability than the soil P fertility status itself. These four characteristics permit the application of a functional and dynamic model for available soil P.

Extraction methods as used in soil routine analysis only allow the determination of a quantity factor. The performance of a new chemical method, the Pi paper method was assessed by comparison with the IEK-method. In the Pi paper method phosphate ions are adsorbed by the iron hydroxide fixed on a filter paper which acts as a sink. In two experiments, the quantities extracted by the Pi paper were compared to the $E_1$ quantities. In the first case, 20 soils from Poland, of similar pedological characteristics were tested using both methods. Three treatments were applied: no P, water-soluble P(TSP) and water-insoluble P fertiliser as phosphate rock. In the second case, five soils, of which three were tropical, of very different characteristics and pedological origin and the other two (acid and calcareous) from continental temperate areas were treated without and with P (PR) application.

For the non-fertilised soils, and those of the similar pedological origin (Poland) which received P, the determination coefficient, $r^2$, of the linear regression between $E_1$ quantities and the quantities extracted with the Pi paper reached 0.95. For the 5 soils from very different pedological origin and treated with phosphate rock, $r^2$ decreased significantly. Close examination of these results showed that this $r^2$ decrease resulted from only one soil. It was found by labelling the isotopically exchangeable fraction of soil-P, that Pi paper extracted between 22 % to 66 % of the isotopically exchangeable P. It can be concluded that: (i) the Pi paper was an efficient method to assess available soil P but it still provided only information on the quantity factor (ii) The Pi paper method like any extraction method has to be calibrated for each soil type.

Assessing fertiliser effectiveness. There is no standard definition of the fertiliser effectiveness. When using isotopic methods, the effectiveness of a P fertiliser, or more generally of a P application, is easily characterised by measuring phosphorus derived from the applied fertiliser (Pdff %), i.e. the contribution of the applied P to the P nutrition of the plants. It was shown that, following a P application: (i) the Pdff % in plant was the same than that of P in the soil solution and (ii) that, if P is the major limiting factor in the soil-plant system, a yield increase can be expected when Pdff % is higher than 30 %. Therefore, it is possible to forecast the effectiveness of a P fertiliser from the Pdff % in soil solution using formula [1]:

$$[1]$$
\[ \text{Pdff} \% = 100 \left( \frac{E_{1F} - E_{1C}}{E_{1F}} \right) \]  \[1\]

where \(E_{1F}\) is the instantaneously isotopically exchangeable P in a soil where P has been applied, and \(E_{1C}\) is the instantaneously isotopically exchangeable in the control soil.

This method was applied to determine the effectiveness of various phosphate fertilisers added to the 250 soils previously analysed. P was applied as water soluble P or as phosphate rock at rates between 0 and 50 mgP kg\(^{-1}\). Soil and phosphate fertilisers were incubated during one month in wet conditions. The decrease of \(E_{1F}\) can be determined for any time \(t\) [days] of contact between soil and fertiliser using formula \(2\):

\[ E_{1F} = E_{1F(t=1)} \left[ t^m \right] + E_{1Feq} \]  \[2\]

where \(E_{1F(t=1)}\) is the value of \(E_1\) in the fertilised soil 1 day after the P application. Thus \% Pdff can be expressed as follows:

\[ \text{Pdff} \% = 100 \left[ \frac{E_{1F(t=1)} \left[ t^m \right]}{E_{1F(t=1)} \left[ t^m \right] + E_{1C}} \right] \]  \[3\]

This relation shows that Pdff \% decreases when: (i) \(E_{1C}\) increases and (ii) contact time \(t\) increases.

This method was used to study the benefits of the soil P recapitalization concept through the application of high rates of phosphate rocks. Soils received 0 or 1000 mgP kg\(^{-1}\) as phosphate rock and were incubated for one month in wet conditions. Additional 50 mgP kg\(^{-1}\) were applied as TSP to the two previous treatments after the incubation period. It may be concluded; i) that heavy applications of phosphate rocks can significantly increase available soil P but to a lesser extent than water soluble P fertilisers; (ii) they do not decrease significantly the fixing capacity of the soil for phosphate ions. In conclusion the recapitalization of the soil P fertility has to be assessed in each particular situation. These conclusions are in full agreement with most of the results obtained by other contractors of this CRP.

**Contributions to the CRP.** The results obtained by the isotope exchange method (IEK) during the 5 year period of the CRP contributed to the development of a phosphate management programme by increasing the knowledge of soil-fertiliser P-plant relationships and its transfer through the application of this knowledge in the improvement of integrated soil, nutrient and crop management practices of farming systems.

1. **Technology development.** Some counterparts were successful in applying the IEK method in their laboratories by refining the protocols and utilising the sensitive green malachite method developed for this objective. This contributed to increased knowledge of soil-fertiliser P-plant relationships.

The IEK method, based on the Brownian motion, is an universal method. Therefore, it was considered as the reference method to characterise available soil P and effectiveness of P fertilisers. Since radioisotopes of P (i.e., \(^{32}\)P, \(^{33}\)P) cannot be used in routine soil analysis simplified models were developed. As the capacity factor of soils is not significantly modified by standard P applications, \(E_1\) and \(C_P\), the phosphate ion concentration in the soil solution, are almost proportional. Thus, formula \([1]\), \([2]\) and \([3]\) can be applied using the \(C_P\) values instead of the \(E_1\) values. Nevertheless, the determinations of \(C_P\) values require very clean laboratory conditions which are not always reached in routine analysis laboratories. Furthermore, as \(E_1\) values and quantities extracted with Pi paper were highly correlated in most cases, the quantities extracted with Pi paper can be used in formula \([1]\), \([2]\) and \([3]\).
2. Technology transfer. With the help of the isotope method it was generally observed, that 20 % of the applied P is taken up by the first crop, and the remaining 80 % of the applied P reacts with the soil components, being mostly unavailable for the following crops. Thus in a given cropping system the fate of P is mainly determined by the amount and the chemical form of the applied P fertiliser and the depth of mixing between soil and fertilisers. Some plant genotypes are able to utilize sparingly soluble forms of P.

Evaluation of available soil P as affected by phosphatic fertilizers, particularly rock phosphates, by biological and chemical methods

Mariusz Fotyma

Phosphatic fertilisers are applied to contribute directly to the P nutrition of the crops and to increase the soil fertility with respect to available phosphorus. Unprocessed apatite and rock phosphates are recognised as a much poorer direct source of phosphorus than superphosphates, but it is assumed that they can increase the pool of available phosphorus particularly in moist and acid soils. The availability of phosphorus in soils, both native and from applied P fertilisers, can be quantitatively determined by means of chemical extraction, adsorption on paper strips Pᵢ, exchange with resins Pₑₓch and isotopic exchange kinetic. The most cumbersome procedure for such evaluation are the biological tests with plants. The aim of these studies was to compare several methods of estimation the soil and fertiliser-derived phosphorus availability for Polish conditions.

Experimental methods

Superphosphate and different rock phosphates (North Carolina and Tunisia in 1997 and 1998 experiments, plus Kola, Togo and Morocco in 1997 experiment) were incubated with the samples of 20 representative soils of Poland for 100 days at room temperature. Afterwards the soil P availability was determined by several chemical methods (Egner – Riehm DL, 0.01 M. CaCl₂, paper strips Pᵢ, anion membrane Pₑₓch and Bray – Kurtz and Olsen – in 1997 only) and isotopic exchange kinetic. In 1997, a short–term vegetation experiment was carried out in incubated soils with 3 test plants.

Results obtained

The recovery fraction of phosphorus from superphosphate amounted to about 50 %, 20 % and 10 % by Egner – Riehm method, Pᵢ paper method and CaCl₂ method, respectively. The recovery fraction of phosphorus from North Carolina and Tunisia rock phosphates was by several times lower. Hence, rock phosphates are ineffective with regard to the increase of the content of available P in the soil. The rate of enriching soils with phosphorus from superphosphate was positively correlated with soil pH and the content of ‘native’ phosphorus. The best, single, methods for estimating the available soil phosphorus were Egner – Riehm DL and the Pᵢ paper. The amounts of phosphorus extracted by means of chemical and isotopic methods were highly correlated. Of particular interest were the close relations between the amount of phosphorus extracted with paper strips Pᵢ and quantity parameter E, as well between the amount of exchangeable phosphorus Pₑₓch and intensity parameter Cₛ.
Conclusions

1. The P recovery coefficient from finely ground ‘soft’ phosphates was several times lower than that from superphosphate. Hence rock phosphates cannot be recommended for direct use in Polish agriculture.

2. For the classical soil testing analysis of the so called available nutrients, the officially used Egner – Riehm DL method was the most suitable for Polish soils. It was the only method, as well, useful in case of fertilising the soils with rock phosphates.

3. Isotopic exchange kinetic method provided the most comprehensive characterisation of soil phosphorus availability (intensity, quantity, buffer capacity parameters ). For routine analysis paper strips P$_i$ and anion membrane P$_{exch}$ methods , applied jointly, can partially substitute the isotopic exchange kinetic.

Studies on alternative phosphorus fertilizer sources for cropping systems grown in Red Ferralitic soils using nuclear techniques

José Alfredo Herrera Altuve

A major constraint to food production in the central region of Cuba is the P deficiency (total and bioavailable P) and the high P sorption capacities of the Red Ferralitic soils. Adequate P fertilisation is essential, but the use of water-soluble P fertilisers has been limited by their cost. Phosphate rock (PR) deposits occur in several regions of Cuba, however, most of these PRs are not effective in neutral and alkaline soils. Partial acidulation of PR improve their effectiveness in soils with pH higher than 6. Accordingly, the objective of this study was to assess the agronomic effectiveness of different PRs products, including the evaluation of methods for quantifying bioavailable P in soils amended with those PRs products.

Experimental methods

Two Ferralsols with pH 6.8 - 7.1 and available P (Olsen): 2.14 - 5.9 mg P kg$^{-1}$ were used. Laboratory studies, incubation trials, greenhouse and field experiments, with sorghum, sugar cane and common bean were carried out. Chemicals methods (Bray I, Olsen, Oniani, Mechlich and Resin) and radiochemical methods (Fardeau et al., 1991; Morel and Fardeau, 1987) were used and/or evaluated for quantifying bioavailable soil P. Six phosphates rocks and their modified products from Cuba and overseas and water-soluble phosphate fertilisers were tested.

Results obtained

Oniani and Bray I methods were good descriptors of available P on the studies when water soluble P fertilisers were used any of the chemical methods tested did not perform well in soils amended with PRs because less than 10% of the P extracted was bioavailable. The $^{32}$P isotopic exchange kinetic method provided more reliable and accurate information. Using
these methods, banding application of superphosphate to each crop in different crop rotations was better than broadcasted P application at the beginning of the rotation.

Natural PRs from Cuban (Higuanojo, La Pimienta and Trinidad de Guedes) and Venezuelan (Riecito) deposits were not effective to increase soil P status. TPS was the best P source and North Carolina PR showed chemical and radiochemical values close to Triple Superphosphate (TSP). PAPRs effectiveness was higher than natural PRs but lower than TSP. Nevertheless, the soil P status values were lower than the sufficient ones under which P will not limit crop yields. Kinetic values were considered not limiting. % Pdff and % RAE were 45 and 59, respectively with Trinidad de Guedes (T de G) PAPR (40-60%). Greenhouse and field experiments confirmed that natural T de G PR was not suitable for direct application to Ferralsols in Ciego de Avila. Trinidad de Guedes PAPR was found to be highly effective comparing to its natural PR when evaluated in terms of dry matter production, plant P uptake and isotopic parameters. It was found that the residual effect of the PAPRs (and North Carolina PR in sugar cane) was greater than that of TSP. With common bean, the effectiveness of TSP was better than T de G PAPR, which in turn, was better than the natural PR. Further, field trials are needed to confirm these results from the greenhouse.

In conclusion, Cuban PRs are not suitable for direct application to Ferralsols with pH higher than 6, though it is possible to enhance their agronomic effectiveness through partial acidulation (40 - 60%). These cost-effective modifications of PR show promise as appropriate technologies for local utilization by farmers in Cuba.

**Chemical characterisation of the soils used for experiments by contractors of the CRP. Methods of analysis. Comparison of available P measurement methods**

Denis Montange

As part of the activity plan of a networked research project on the agronomic effectiveness of P fertilizers, in particular rock phosphates, the Soils and Fertilisers Laboratory of CIRAD, Montpellier, France performed the standard soil characterisation in 57 benchmark soil samples from 16 countries: Austria (4), Belarus (1), Brazil (2), Chile (3), China (20), Cuba (1) Ghana (6), Hungary (3), Indonesia (3), Kenya (1), Malaysia (1), Poland (1), Romania (2), Russia (1), Thailand (4) and Venezuela (4). These analyses were carried out with the financial support of the World Phosphate Institute (IMPHOS).

The analyses done for the soil characterisation were: granulometry, pH, chemical analysis for total elements and exchangeable ones (CEC, base saturation). Available P was measured using 3 methods: Olsen, Bray II and Pi paper. These results will be compared with those done by T. Muraoka (CENA, Piracicaba, Brazil) in the same soil samples using the resin method and J.C. Fardeau (CEN Cadarache, France) using the $^{32}$P isotopic exchange kinetic method. Furthermore to calibrate these methods of measurement of bioavailable P, all these results should be related to the field data (dry matter and commercial yield) and to the type of soil.

From the results of the soil analyses, it was considered that the soil conditions suitable for a direct application of PR were: low available P, acid pH (<6.0) for a better dissolution of PR, low base saturation of the CEC. The granulometric analyses of the samples showed a great range of textural classes: the sandy fractions (coarse and fine ones) represented from
4.5% to 89.6% and the clays from 5.9% to 70.5%. A high content of clay may correspond to a high sorption potential of the soil for soluble P. Organic matter ranged from 0.38% to 20.43% (the latter value corresponded to a soil sample from Poland).

The CEC values ranged from 0.7 to 35.8 meq/100g and the percentage of base saturation from 8 to 100%. The pH \( \text{H}_2\text{O} \) in the 57 samples varied from 4.20 to 8.95; of which 36 samples had \( \text{pH} < 6.0 \). As a first approximation, it is expected that these acid soils will have adequate conditions for PR dissolution; this should be checked further in the contractors' reports.

18 soil samples showed a percentage of base saturation lower than 70% and 17 of them had a \( \text{pH} < 5.0 \), which are both good conditions for PR dissolution but these soils had also a very low CEC (<10 meq/100g).

The total P of the soil samples ranged from 63 to 1893 mg/kg. According to the Olsen method, the available P varied from 1.6 to 98 mg/kg and 56% of the soils had a P Olsen < 10 mg/kg, which is generally considered as deficiency level. For Bray II, the range was from 2.2 to 427.7 mg/kg. The values for the Pi paper method varied from 0.1 to 44.4 mg/kg. From the results obtained it may be inferred that these 3 methods are extracting various pools of soil P. In order to calibrate the results of P extracted by these chemical methods and to assess the P actually bioavailable, the crop response to the P fertilisation is needed.

The use of nuclear and related techniques for evaluating the agronomic effectiveness of phosphate fertilisers, in particular rock phosphates, in Brazil

Takashi Muraoka

A series of experiments most of them using \(^{32}\text{P}\) isotope techniques was carried out in Brazil during the period 1993-98, within the frame of an IAEA/FAO Co-ordinated Research Project on the agronomic effectiveness of P fertilisers.

Initial studies were carried out to obtain some basic information required to get a better understanding of dynamics of P in tropical soils, i.e. a) methods for evaluating available P in soils amended with different P sources, including water insoluble ones; b) P availability from different solubility phosphates applied to tropical soils after variable period of incubation; c) efficiency of different P sources and d) fate of liquid and solid P fertilisers in the soil. The main results can be summarised as follows: a) Mehlich 1 which is the official Brazilian (except S. Paulo State) method for soil P testing is not adequate for soils amended with PR; b) the Bray 1 method was the extractant which gave better correlation with plant P uptake in soils amended with different P sources, including PR, and gave similar performance to E value; c) the use of \(^{32}\text{P}\) labelled fertilisers permitted to follow the fate of several P fertilisers in inorganic soil P fractions The predominant forms recovered were Al and Fe bound fractions; d) in five soils from the Amazon region, TSP and thermophosphate were the best sources of P, but North Carolina phosphate rock and coarse thermophosphate showed good residual effect; e) in these soils, Mehlich 3 and Bray 1 extractants were more sensitive to detect soil P variations; f) the Patos PR, even applied at very high rate, was very ineffective and its availability did not increase with the duration of the incubation period, as probably the reverse (fixation) reaction in the soil is a more rapid and intensive process than the dissolution process.
Due to the low effectiveness of Patos PR applied directly, experiments were carried out to enhance its effectiveness. One strategy consisted of applying Patos PR with water-soluble P sources (TSP or SSP). Mixing intimately Patos PR with TSP or SSP increased considerably its P availability. This effect was probably due to the residual acidity of TSP or SSP, which continued to solubilize the PR phosphorus, as the effect was not observed when the P sources were applied separately.

Another alternative, which came upon, was the utilization of plants/crops considered to have the capability to utilize P from insoluble sources such as PR. Eucalyptus was selected for this purpose. The results obtained using $^{32}$P labelled mono-, bi- and tri-calcium phosphate in a greenhouse study showed that eucalyptus was even less effective than rice and also soybean, which is considered less tolerant plant to P deficiency. Eucalyptus seems to be very little demanding in P in its initial stages of growth. Similar results were observed in the field experiments.

All this information generated from this project will certainly contribute to a better use of P fertilisers for increasing crop productivity in the tropical soils of Brazil.

**Effect of Phosphate Rock Fertilisation and Arbuscular Mycorrhizae (AM) Inoculation on the Growth of Agroforestry Tree Seedlings**

Nancy K. Karanja and Kaleb Adamba Mwendwa

Phosphate rock (PR) have been identified as cheap complements of water-soluble phosphate fertilisers for low pH soils. Arbuscular mycorrhizae (AM) improves plant uptake of P and other nutrients in acidic, low-P soils. Using two acid soils of Kenya (Acrisols and Andosols), a two studies were carried out to evaluate effect of Minjingu Phosphate Rock (Minjingu PR) on growth of four (4) agroforestry multipurpose trees, *Leucaena leucocephala*, *Cassia siamea*, *Grevillea robusta*, and *Eucalyptus grandis*. In the first experiment one month old seedlings received Minjingu PR at 0 (PR0), 51.6 (PR1) and 77.4 (PR2) Kg P ha$^{-1}$ in 2 Kg soil. In the second experiment the Minjingu PR rates of the first experiment were maintained, *G. robusta* and *L. leucocephala* were the test crops and only the Acrisols (10 kg) were used. A-mycorrhizae inoculum in the form of mixed soil and roots was included in this study. There was a slower response to Minjingu PR fertiliser application in Andosols as compared to Acrisols. At 19 weeks after transplanting (19 WAT), PR2 had caused a significant (p < 0.05) height increase over PR0 for *L. leucocephala* and the heights where PR was added differed significantly (p < 0.05) from PR0 in root collar diameter (rcd) for *G. robusta* in Acrisols. Addition of PR2 had a negative effect on height of *C. siamea* whereas *E. grandis* did not respond to PR additions. Application of PR in Andosols, significantly reduced (p <0.05) height and root collar diameter of *G. robusta* and *C. siamea* as compared to the control. In the second study, there were significant increases of up to 121% in height (p <0.001) and root collar diameter (p < 0.05) and 4.5 times biomass over the controls where *L. leucocephala* seedlings received rock phosphates alone and PR+mycorrhizae at 12 months after planting. Nodulation of *L. leucocephala* was significantly affected by P application and/or AM-mycorrhizae inoculation but was variable within any similar treatments except for controls,
where no nodulation was observed. Species x treatments interactions were significant, p<0.05 and p<0.001 for shoot and root dry weight respectively. It is probably not necessary to add Minjingu PR fertiliser to *G. robusta* in either soil and to *C. siamea* in the Andosols soils. PR and mycorrhizae inoculation have the potential to improve legume performance in these acidic soils. However more studies are required to study PR availability to the tree species.

Furthermore, a greenhouse experiment was conducted to evaluate availability and uptake of phosphorus (P) from Minjingu phosphate rock (MPR). An acid soil and six agroforestry tree species namely *Leucaena leucocephala*, *G. sepium*, *S. sesban*, *G. robusta*, *C. siamea* and *E. grandis* were used. Phosphorus was applied at 129 mg P/5 kg soil as Minjingu phosphate rock (MPR) or Triple Superphosphate (TSP). P-germinated seedlings were transplanted and divided into two sets for sequential harvests at 3 and 6 MAT (months after transplanting). 32P labelled carrier solution was added to transplanted seedlings at the beginning and when they were 3 months old for each of the sets under study. The soil was tested for isotopically exchangeable P by incubating the soil solution with the MPR and TSP. The soil was high in P fixing ability. At 3 MAT all the species except *G. robusta* gave a 150 -250% significantly higher stem dry weights where P was added and *L. leucocephala*, *S. sesban* and *C. siamea* showed this response up to 6 MAT. All the legumes and *E. grandis* where P was applied differed significantly from controls in root dry weight with Minjingu PR being superior with *G. sepium* and *E.*. The legumes and *E. grandis* had significantly higher P uptake where P was applied at 3 MAT. The relative availability of MPR at 3 MAT showed that *L. leucocephala* and *G. sepium* derived 2.93 and 1.06 times more P from Minjingu PR than from TSP respectively. P uptake data from *G. robusta* showed that this species prefered soil P to externally supplied P in the three sampling periods. Tree species and fertiliser P interactions at 6 MAT were highly significant (P=0.01). Vascular arbuscular mycorrhiza (VAM) inoculation improved growth, P uptake from MPR and nodulation of *G. sepium* seedlings. Inoculating *L. leucocephala* seedlings with VAM increased availability of P from MPR.

**Assessment of the Relative Agronomic Effectiveness of Phosphate Rock Materials in a Soybean - Maize Crop Rotation Using Isotope Techniques**

*Jittiwan Mahisarakul, Chantana Siri aibool, Jittra Klaimon and Phannee Pakko*

A series of laboratory, greenhouse and field experiments were carried out with the following objectives: (1) to determine the relative agronomic effectiveness (RAE) of various phosphate rocks in a crop rotation of soybean-maize in acid soils of Thailand, and (2) to obtain information on the ability different phosphate materials to supply P to acid soils of Thailand. This research work was done in three phases.

**Phase I.**

**Laboratory test.** Six acid soils were used from different benchmark sites in Thailand. Two Thai phosphate rocks (PRs) (Lumpung PR (LPPR) Ratchaburi PR (RBPR)) as well as triple superphosphate (TSP) were applied in order to characterised the P dynamics of these soils using P-32 isotope exchange kinetic technique (E1 value). It was found that soils in terms of P-fixation ranked in the following order: Mae Tang > Rangsit > Pakchong > Korat > Warin soil.
Pot experiments. Seven soybean and five maize cultivars were screened for P use efficiency in Hoagland solution with various P concentrations. The most tolerant to low P soybean and maize cultivars were Nakorn Sawan I and hybrid 35 respectively.

Phase II.

Greenhouse experiments were conducted for two years to assess RAE of PR materials in a soybean-maize rotation, using P-32 isotope dilution techniques. The crops were grown in pots with four acid soils. In the first year, TSP at four increasing rates and four PRs at one rate were used. Soybean did not respond to P application from TSP, but there was a good response in maize, which was planted after soybean (1st residual effect). For soybean the percent P derived from TSP or PR fertiliser (%Pdff) was in the following order: Warin soil > Mae Tang soil > Rangsit soil > Pakchon soil; for maize, it was Warin soil > Pakchong soil > Mae Tang soil Rangsit soil.

In the second year the soybean-maize rotation was replanted to study the residual effect of TSP and PRs, both applied at 180 mg P kg\(^{-1}\). This greenhouse experiment indicated no significant response of soybean to TSP in terms of dry matter yield. In terms of %Pdff, %FPU (% Fertiliser P utilisation) and %RAE the soils ranked as follows: Rangsit soil > Pakchong soil > Mae Tang soil > Warin soil. The same results were obtained in maize. Both crops absorbed more P from TSP than from PRs.

Field experiment. Three rates of TSP and one rate of each of the same PRs previously used in the greenhouse experiment, were applied to the Pakchong soil. At harvest, soybean had absorbed more P from TSP fertiliser (%FPU) applied at 40 mg P kg\(^{-1}\) than maize, but there was no yield response. Among four PRs, North Carolina phosphate rock (NCPR) had the highest % Pdff as well as the highest RAE. Maize was planted after soybean to study the residual effect of TSP and PRs. The results were similar to those found for soybean.

In the second year the grain yield of soybean was higher than in the first year, and there was significant response to P from TSP. The RAE of NCPR was very high. Maize showed the opposite results. In this case the Algerian PR (ARPR) had the highest RAE.

Phase III.

The best treatments from the previous phase were used.

Greenhouse experiment. One rate of P for both TSP and PRs were applied to two acid soils. PRs were applied either alone or in combination with TSP (50:50). Soybean was planted first, followed by maize. The P-response in terms of dry matter yield, %Pdff and %FPU was highly significant in both soils. RAE ranked as follows: TSP > NCPR + TSP > LPPR + TSP > NCPR > LPPR. Maize showed the same trend in RAE as soybean in both soils. The RAE for both crops were highest in Warin soil.

Field experiment. TSP and six PRs were applied at 60 kg P ha\(^{-1}\) to the Pakchong soil. The application of TSP resulted in high yields of soybean. In terms of RAE, the P sources ranked as follows: LPPR + TSP > ARPR > LPPR > MCPR > NCPR + TSP > NCPR. The residual effect of P on the following maize crop resulted in a high RAE for MCPR (Morocco PR) and LPPR. It was concluded that TSP should be applied to every crop. The reactivity of PRs were: ARPR > NCPR > RBPR > PBPR; MCPR and LPPR were also rather reactive. The combination of PR and TSP resulted in better P uptake from fertiliser (%Pdff).

Isotopic and conventional procedures to determine availability of phosphorus, cadmium and fluorine in soils and crops fertilised with soluble phosphorus fertilisers and reactive phosphate rocks

M.J. McLaughlin and Daryl Stevens

Activities under this IAEA project were closely co-ordinated with the National Reactive Phosphate Rock (RPR) Project in Australia administered through La Trobe University in Melbourne, Australia. Work was divided into a number of phases. Initial experiments were designed to assess the efficacy of isotopic and non-isotopic techniques to assess phosphorus (P) fertility of soils and the capacity of soil tests to predict response to P fertilisers and reactive phosphate rocks under field conditions. Subsequently, work focused on the assessment of potential adverse environmental effects of impurities of Cadmium (Cd) and Fluorine (F) in phosphate rocks and fertilisers.

Pasture response to soluble P and phosphate rock fertilisers was assessed at 30 sites around Australia and soil tests related to plant responses. All tests, including isotopic procedures, performed poorly under the wide set of growing and soil conditions under which the tests were assessed. Isotopically-exchangeable P (E values) determined using shorter equilibration times was better related to pasture responsiveness to P, and hence fertiliser P requirement, than E values determined using longer equilibration times. Errors in abnormally high E values in some soils were found to be caused by low precision in determination of solution P concentrations at levels less than 0.02 mg P/L.

Environmental concerns relating to Cadmium (Cd) and Fluorine (F) in phosphate rock fertilisers were assessed at 11 and 4 sites, respectively, of the National Reactive Phosphate Rock (RPR) Project. There were no significant differences between F in herbage from plots fertilised with either single superphosphate, partially acidulated phosphate rock or North Carolina phosphate rock, or between sites. Concentrations of F in herbage were low, generally less than 10 mg F/kg. However, there were large differences in Cd concentrations in herbage between sites, while differences between fertiliser treatments were small in comparison. The site differences were only weakly related to total or extractable (0.01 mol/L CaCl₂) Cd concentrations in soil. Significant differences in Cd concentrations in clover due to fertiliser type were found at 5 sites. North Carolina phosphate rock treatments had significantly higher Cd concentrations in clover compared to single superphosphate at 2 sites. Partially acidulated phosphate rock treatments had significantly higher Cd concentrations in clover compared to single superphosphate at 4 sites. At the site where Hemrawein was tested, this treatment had significantly lower Cd concentrations in clover compared to both single superphosphate and North Carolina phosphate rock treatments.

At one pasture site, long-term reactions of fertiliser Cd in soil were measured using ¹⁰⁹Cd. Accumulation of Cd in the soil was highly correlated to application rate of single superphosphate. No evidence was found to indicate offsite movement of Cd, either through horizontal transfer or via leaching through the profile. Increases in soil Cd led to an increase in the Cd content of wheat which was grown in the soil. However, using a radioisotope dilution technique, a significant proportion of the added Cd was found to exist in a non-bioavailable pool in the soil. A model was developed which estimated that Cd was being fixed in this soil at a rate of 1 to 1.5 % of the total added Cd per year.
Evaluation of phosphate fertilisers in acid soils of Hungary

Tamas Nemeth

Scientific background and scope of the project: In the fertilisation practice of Hungarian agriculture mainly superphosphate has been applied as P fertiliser on both calcareous and acidic soils. Few earlier investigations have been conducted with rock phosphates as follows: i) Laboratory analyses: solubility of rock phosphates in water, citric acid, etc.; specific surfaces of rock phosphates, etc., and ii) Pot and field trials comparing the effect of rock phosphates with the effect of superphosphate on yields and P uptake by crops.

1. Continuation of two comparative field trials

Small plot (100 m²) field trials were laid down in 1994 on two characteristic Hungarian acidic soils to compare the effect of granulated Kola single superphosphate (SSP) and ground (average particle size: 63 µ) reactive Algerian rock phosphate (APR).

The trials were set up in a randomised block design comprising 6 P treatments in 4 replications, for a period of 5 years. The 5-year effects of a yearly application of 80 kg/ha P₂O₅ (5x80=400) were to be compared to the residual effects of the initial build-up dose of 400 kg/ha. The indicator crops were spring and winter barley, winter wheat, maize and peas.

The AL-extractant (Egner, Riehm and Domingo 1960) with its acid reaction (pH 3.75) dissolved more P from the rock phosphate treated soils than from the superphosphate treated ones. In contrast to the AL-P contents, Olsen P values were much higher in the superphosphate treatments.

There were no detectable increases in neither the LE (Lakanen-Erviö)-Cd nor in the LE-Cr contents as an effect of Algerian rock phosphate application. The LE-Sr content of the build-up superphosphate treatment, however, increased significantly as compared to the P control or the Algerian rock phosphate treatments.

From the grain yield results of the first four years we can state that the responses to P were related to the original soil P level: on the average the highest yield increases in cereal units (0.6 to 0.8 t/ha, or 12 to 17%) were reached in the Kompolt soil of poor-medium original soil P supply, while only half of these values (0.3 to 0.4 t/ha, or 7 to 12%) were obtained in the Szentgyörgyvölgy soil of medium-good P supply.

Based on the results of the first four years there were, practically no differences in the effect of the yearly P fertilisation and in the residual effect of the initial build-up P doses, resp. The residual effect was slightly (about 1-2%) higher than the effect of yearly application. The final evaluation, however, will be done made after the 5th year.

Shoot and leaf P concentrations at flowering stage were not increased as an effect of P fertilisation. It seems that a better P status increased young plant weights rather than their P%.

Increase in grain P concentrations was less expressed, than in the grain yields. The better P status resulted in an increase in grain yields, but not in the grain P%.

P uptake of the above-ground parts at harvest time showed similar trends to the grain yields. Phosphorus given to the crops during the first four year period was utilized moderately. In the Kompolt soil, which is originally poorly-moderately supplied with phosphorus, the apparent P utilization was almost three fold higher (7-8%) than that (2-3%) in the Szentgyörgyvölgy soil of originally medium-good P supply.

Negative high values for P balance (-170 kg/ha) were calculated for the P control plots only.
receiving NK. There was no difference in the positive P-balances as an effect of the different P forms. Build-up and yearly P application will be compared only after the 5th year.

Responses to the two P sources was related to the soil P availability of the two sites.

The positive P-balances on the P treatments indicate that after the fifth year of the trial significant P residual effects are to be expected and thus the P utilization can be increased furthermore. Responses to reactive Algerian rock phosphate were similar to that of single superphosphate. Reactive rock phosphates are economic alternative P sources for the moderately or strongly acidic Hungarian soils.

2 Comparison of the Effect of Phosphate rock and Superphosphate in Incubation and Pot Experiments

In incubation and pot experiments, the effects of a phosphate rock from Algeria and a single superphosphate from Russia on the changes in available P and yield and P uptake of winter rape were studied in two acidic soils of Hungary. The soils included in the experiments were a moderately acidic pseudogley brown forest soil (Szentgyörgyvölgy) and a slightly acidic chernozem brown forest soil (Kompolt). The experiments were set up with similar P active agent contents.

In the incubation experiment the soil water content was set at 30 and 50 % of maximum water capacity, the temperature range was between 25 and 40°C. The changes in water-, ammonium lactate-soluble P (AL-P) contents and the pH (H2O) with time were measured.

The water-soluble P content in Szentgyörgyvölgy soil was influenced both by the P form and experimental conditions at the beginning of incubation. After the 15th-20th day-when the rapid sorption process of water-soluble P fertiliser ended - the effect of P form decreased.

The water-soluble P content decreased with time, and this decrease was different - due to the effect of experimental conditions - in the phosphate rock- and superphosphate-treated soils.

The water-soluble P content in the phosphate rock-treated samples was affected to a great extent by soil water content, while incubation temperature had a greater effect in superphosphate treated soils.

In Hungary, the AL-extractant has been used conventionally to assess soil P availability. At the beginning of incubation equal rates of phosphate rock and superphosphate had a similar effect on the AL-soluble P content of soils. The AL-soluble P content of phosphate rock-treated soils was higher throughout incubation. The AL-soluble P content of the superphosphate-treated soils decreased to a greater extent in the first period of incubation than that of the control and phosphate rock-treated soils. Temperature had a greater effect on AL soluble P content of soils than soil water content.

According to our experimental data the AL-method is not appropriate for soil testing of available P from phosphate rocks. Similarly to the Bray II and double-acid methods, the AL-extractant can dissolve a substantial amount of the undecomposed phosphate rock during extraction and thus can overestimate the available P form from phosphate rock-treated soils as compared to that from single superphosphate.

The initial pH of soils decreased by 0.5 on the average in the superphosphate treatments. Phosphate rock slightly increased the pH of Kompolt soil. The increase in Szentgyörgyvölgy soil was greater, however, no ‘liming effect’ could be observed.

In the pot experiment the effects of P forms and P doses were compared in the incubated and non-incubated (fertilisers were freshly mixed into the soil) samples of the two
soils with winter rape as test plant. These factors had different effects on dry matter yield, P concentration and P uptake of rape plants in the two soils.

Increment P doses in Szentgyörgyvölgy soil increased only the plants’ P concentration, while in Kompolt soil dry matter yield, P concentration and P uptake of winter rape were increased. These increases were higher in the superphosphate treatments.

In the Szentgyörgyvölgy soil, incubation significantly decreased all three plant parameters. In the Kompolt soil, however, the incubated superphosphate treatments produced the higher winter rape yield.

In the Szentgyörgyvölgy soil, phosphate rock influenced the dry matter yield, P concentration and P uptake of winter rape similarly to superphosphate. In the Kompolt soil, superphosphate was the most efficient P fertiliser, resulting in significant increases in the P concentration and P uptake of winter rape.

Isotopic exchange kinetics and P fertilizer efficiency in volcanic ash-derived soils (Andisols and Ultisols) from Chile

I. Pino, W. Luzio and A.M. Parada

Ten representative volcanic ash-derived soil samples from the surface horizon were taken in the X Region. These soils had an acid pH, a high P retention capacity (Blakemore method) and low to medium available P (Olsen). The organic carbon is high to very high and the C/N ratio is high.

Four soil profiles were sampled in the IX Region. As in the X Region, the C/N ratio was very high. P retention is over 85% in all soils, except in one classified as Palehumult (Metrenco soil Series). Nevertheless, P retention values, from 72.1% to 78.6%, are considered very high figures for a non-volcanic ash-derived soil. In the same way the Al+1/2 Fe (ox) in all profiles showed high values for non volcanic ash soils. These data confirm the extensive and deep cover of volcanic ashes that has been gradually added to the soils of this Region. The P Olsen gave very low values which are normal for Andisols.

A model to forecast the kinetics of P isotopic exchange was applied to the ten soils from the X region of Chile with the aim to characterize the kinetic parameters and the compartmental model of bioavailable P.

The values for the Intensity factor (less than 0.02 mgP L⁻¹ ) were considered as limiting for normal nutrition of crops. Similarly the values between 0.07 and 2.4 mgP kg⁻¹ obtained for Quantity factor were also considered limiting for crop nutrition . The immediately available pool of P was slightly higher in the Crucero soil under fallow than in the other two management systems. The A, B and C pools showed a relatively homogeneous distribution. An increase in the pool D that represents the P immobilized from earlier P applications was observed.

In the Crucero soil under a pine forest the unique source of P for plants came from the pool D, which will decrease gradually as it is absorbed by plants.

In the Crucero soil with wheat, the major fraction of P was found in the pool A coming from the recent application of P fertilizers.

The phosphoric rock from Bahía Inglesa (RBI) had a low efficiency in annual intensive crops, in comparison to permanent crops where it showed a residual effect. In the greenhouse
assays it was found that, in spite RBI is a reactive rock in the volcanic ash soils (Andisols and Ultisols), TSP was better for annual crops.

The Senegal phosphate rock was not efficient in Cunco and Los Prados soils and the Gafsa phosphate rock when compared to RBI was similar in Los Prados but less efficient in Cunco soils. The mixture of TSP and the rocks showed a better efficiency specially for Senegal Rock in Cunco and Los Prados. In Pemehue and Metrenco soils, the mixture TSP+RBI was not efficient as in Cunco and Los Prados soils. Further field studies are needed to confirm these results. A combination of TSP and PR as a mixture may be a promising alternative to crops grown in some of the studied soils.

Current and residual effects of reactive and unreactive natural phosphate rocks on annual crops grown on highly weathered acid soils of Malaysia

Zaharah Abdul Rahman

The fate of phosphate rocks (PR) applied to Malaysian soils have not been studied in detail. The dissolution and agronomic effectiveness of various PR sources of different reactivity is of great interest to the tree plantation sector since they are the major consumer of PR in Malaysia. Thus, a series of greenhouse and laboratory experiments involving conventional chemical extractants and isotopic techniques were carried out to evaluate the agronomic effectiveness of several imported PR sources. The effects of ameliorating the soil with several types of green manures and their effect on PR solubility and P uptake by plants were also studied.

Experimental method

Six sources of PR (from North Carolina, Tunisia, Jordan, Morocco, Christmas Island and China) and triple superphosphate (TSP) were evaluated on a Rengam series soil (Typic Paleudult) with oil palm seedlings as the test crop using the P-32 isotopic dilution technique. Plant growth, P uptake with time and P dissolution of these PR was assessed using 0.5M NaOH, 2% citric acid, 2% formic acid, 0.5M ammonium citrate, L-value and E-value. The effects of different sources of green manures on PR dissolution and P uptake by plants was also evaluated using the P-32 isotope dilution technique with sweet corn as the indicator crop.

Results obtained

PR reactivity ranked according to CaO:P2O5 molar ratio and the magnitude of PR solubility in 2% citric acid and 2% formic acid and neutral ammonium citrate as percentage of rock and total P2O5 were in the order of NCPR > TPR > JPR > MPR > CIPR > CPR. Correlation coefficients of P extracted by these three methods to total P taken up by one-year old oil palm plants showed that neutral ammonium acetate gave the highest r² value as compared to 2% formic acid or 2% citric acid. The r² also improved when the solubility of the PR were expressed as percentage of the rock rather than total P2O5 content. The P uptake in the first 3 months were almost similar among the PR tested. The uptake increased with growing time with NCPR and TPR showing higher P uptake as compared to
CIPR and CPR. More than 80% of the total P in the plant was derived from the fertilisers added, with TSP being the highest contributor of P towards plant P (> 96%).

In the green manure experiment, plants treated with CPR without the addition of green manures gave the lowest P derived from fertiliser (PdfT). The highest PdfT was shown by plants treated with APR. The addition of G. sepium generally increased PdfT of most of the PR treatments, especially from CPR and TPR. The application of green manures generally depressed the PdfT values of APR and TSP whereas the effect of L. leucocephala on the latter was significant. The highest decrease in P derived from APR was from the addition of A. mangium, while for TSP, L. leucocephala treatment.

0.5N NaOH was found to be better extractant in determining the extent of PR dissolution in the soil while neutral ammonium citrate was the indirect method for determining the solubility of these various sources of PR.

The immediate effect of a P fertiliser on dry matter yield and P uptake by plants estimated in greenhouse study depended both on the PR sources used and their contact time with the soil. The P availability from TSP and PR tested decreased with increasing time of contact between soil and fertiliser. The rate of decrease was higher for soluble sources as compared for the less soluble source.

The isotopic technique (E-value or L-value) showed that NCPR and TPR had the highest P utilization as compared to all the other PR from Morocco, Jordan, Christmas Island and China.

The effectiveness of these P sources used for oil palm seedlings can be ranked in the order of NCPR>TPR>JPR>MPR>CIPR>CPR. This ranking is similar to the ranking made from the solubility of these PR by 2% formic acid, 2% citric acid or neutral ammonium citrate expressed as percentage of rock. Ammonium citrate soluble P correlates better to plant P uptake than formic acid or citric acid.

The addition of green manures increased the solubility of the less reactive PR. The solubility of the more reactive PR was either depressed or unaffected, depending on the green manure quality especially C:P ratio.

**Studies on the effect of liming on the effectiveness of Maardu phosphate rock**

Gyidas Sidlauskas and Valensas Ezerinskas

Field experiments were designed for comparing superphosphate and phosphate rock from the Maardu deposit. This phosphate rock was intensively used as P fertiliser in Lithuania. However after the superphosphate production plant was built up, the use of rock phosphate declined almost completely due to the dustiness during the spreading operation.

The experiments were conducted at three levels of acidity: a) unlimed acid soil with a high content of Al (pH KCl 4.3 - 4.4, hydrolytic acidity was 41 - 44 m.ekv/kg soil), b) soil limed with 0.5 rate CaCO₃ powder limestone, and c) soil limed with 1.0 rate CaCO₃. The soil had a sufficient amount of mobile potassium for the growth of plants, but little mobile phosphorus. Lime was applied to neutralise Al toxic to plants and to reduce soil acidity. Granulated superphosphate was utilized in the comparison trials. Crops, responsive to changes in soil reaction were grown in the trials: fodder beets and barley. Moreover fodder beets were chosen because they are fertilised with large amount of mineral fertilisers.
Field experiments were carried out with fodder beets during two consecutive years. In the 1997 trial the yield increased significantly due to liming, however, the application of P fertilisers did not increase significantly the yield. Differences between the effect of superphosphate and phosphate rock were not observed. This might be due to a severe drought that occurred during the vegetative growth of plants. In the following year (1998) a soil with similar acidity was chosen, however it contained even lower amount of available phosphorus in the topsoil (about 50 mg/kg soil). The plant-growing conditions were good and reliable yield data were obtained. In the unlimed soil the yield was generally low and the effect of the superphosphate was better than that of phosphate rock. Average fodder beet yield were good (32 - 35 t/ha) at the low rate of liming and the effect of phosphate rock was better than that of superphosphate. With the high rate of liming (1.0 rate of CaCO3 according to hydrolytic acidity) the effect of phosphate rock declined, and better yields were obtained with superphosphate.

Barley was grown after fodder beets and the effect of superphosphate and phosphate rock was investigated. Weather conditions were favourable for barley growth therefore a normal yield (4.1 - 4.8 t/ha) was obtained in the limed soil. Although yield differences due to different phosphoric fertilisers were small, a significant yield increase through phosphate rock application was obtained in the soil limed with 0.5 rate, as compared to superphosphate. The investigated P sources did not have any effect on fodder beet and barley quality changes. The changes in the yield of the products of the investigated plants were similar to those of the primary yield (barley straw, fodder beet tops).

The Use of Nuclear and Related Techniques for Evaluating the Agronomic Effectiveness of Phosphate Fertilisers, in Particular, Rock Phosphates

Frank J. Sikora

The use of phosphate rock reserves in the United States as a P source for direct soil application is extremely limited in production agriculture. The abundant supply of water-soluble P fertilisers at reasonable costs results in very little farmers choosing phosphate rock as a P source. In addition to the limited use of phosphate rock as fertiliser in the United States, TVA was going through major programmatic changes moving away from fertiliser development and towards remediation of environmental problems. In light of these factors, the focus of the research at TVA was on the use of phosphate rock for remediation efforts. Two studies were conducted to evaluate the use of North Carolina and Idaho phosphate rocks for revegetating extremely acidic soil in the Copper Basin of Tennessee. One study was conducted to evaluate the use of North Carolina and Florida phosphate rocks for treating acid mine drainage that is commonly released from abandoned coal mine sites.

Experimental Methods

Study I – “Effectiveness of North Carolina Phosphate Rock and Fertiliser Tablets in Reclaiming Acidic, Denuded Land in Copper Basin, Tennessee”. A field study was conducted on revegetating acidic denuded soil in Copper Basin, Tennessee with loblolly pines and a variety of ground cover species. The study included 56 plots that
were 7.3 x 9.1 m². Treatments included 3 P application rates of 20, 59, or 295 kg/ha surface applied as North Carolina phosphate rock or TSP, use or absence of fertiliser tree tablets, and a control without surface P application.

Study II – “Evaluating and Quantifying the Liming Potential of Phosphate Rocks”. The calcium carbonate equivalence of a variety of phosphate rocks was evaluated via theoretical calculations, laboratory titrations, and soil incubation. Laboratory titrations were conducted according to AOAC method 955.01. Soil incubations were conducted by applying various quantities of North Carolina phosphate rock, Idaho phosphate, and lime to 100 g of Copper Basin soil with a soil pH of 4.2.

Study III – “Potential Treatment of Acid Mine Drainage using Phosphate Rock” The potential use of phosphate rock for treating acid mine drainage was evaluated via laboratory sorption experiments and microcosm greenhouse study. Florida pebble, Florida trash, and North Carolina phosphate rock were used in the sorption experiments. The microcosm study used Florida trash phosphate rock in sink basins that were 52 x 52 cm² and 30 cm deep. Treatments consisted of a factorial arrangement of 2 flow rates (33 or 100 ml/min) and 2 levels of metal concentration in the simulated acid mine drainage (200, 90, and 60 mg/L Fe, Al, and Mn or 40, 20, and 15 mg/L Fe, Al, and Mn).

Results Obtained

Study I – “Effectiveness of North Carolina Phosphate Rock and Fertiliser Tablets in Reclaiming Acidic, Denuded Land in Copper Basin, Tennessee” North Carolina phosphate rock improved loblolly growth up to an application of 59 kg/ha and was more effective than TSP after 960 days. Phosphate rock also improved ground coverage of lespedeza and black locust. Phosphate rock had a greater influence on increasing soil pH and molar Ca:Al ratios in soil solution and decreasing soil extractable Al compared to TSP.

Study II – “Evaluating and Quantifying the Liming Potential of Phosphate Rocks” Theoretical %CCE in phosphate rocks ranges from 59.5 to 63.1%. The AOAC method 955.01 resulted in %CCE values in North Carolina and Idaho phosphate rocks that were 15 to 40% less than theoretical values due to precipitation of some dicalcium phosphate. Soil incubations showed %CCE of phosphate rocks to be dependent on %P dissolution ranging from 8.5% at 0% P dissolution to theoretical values at 100% P dissolution.

Study III – “Potential Treatment of Acid Mine Drainage using Phosphate Rock” Trash Florida phosphate rock sorbed more Fe than the other phosphate rocks tested. Trash Florida phosphate rock in vertical flow reactors coupled with an oxidation basin did remove Fe, Al, and acidity but did not remove Mn. Phosphate rock layer in the reactor did not remove Al or Mn. Only Fe was removed directly in the phosphate rock.

Conclusions

Study I – “Effectiveness of North Carolina Phosphate Rock and Fertiliser Tablets in Reclaiming Acidic, Denuded Land in Copper Basin, Tennessee”
North Carolina phosphate rock is more effective at improving loblolly pine growth, increasing legume growth, and decreasing soil acidity compared to TSP. North Carolina phosphate rock is well suited as a P source and liming agent in revegetating acidic soil.

Study II – “Evaluating and Quantifying the Liming Potential of Phosphate Rocks”
Theoretical CCE of phosphate rocks ranges from 59.5 to 63.1%. Theoretical CCE are not achieved from phosphate rock application to soil because of incomplete dissolution. The CCE value ranges from 8.5% up to the theoretical values depending on %P dissolution from phosphate rock.

Study III – “Potential Treatment of Acid Mine Drainage using Phosphate Rock”
Vertical-flow phosphate rock reactors with an oxidation basin can effectively remove Fe, Al, and acidity in acid mine drainage at rates of 10, 8, and 3.5 g/m²/d, respectively, when a trash Florida phosphate rock is used. Precipitates clogging in phosphate rock is a serious issue that needs addressed before acceptance of the technology for long-term operation in the field.

The Direct Use of Phosphate Rock to Improve Crop Production in Indonesia

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Most fertile land of Indonesia is currently under cultivation. Due to the urgent need to increase food production for the ever growing population there is a pressure for incorporating marginal soils into agriculture. These tropical soils (mostly Ultisols and Oxisols) are fragile, acid and have several constraints to support food production. One such constraint is the P deficiency. Therefore, P fertilisers must be applied for optimum crop growth and food production.

Attempts were made to develop some P fertiliser management practices in Indonesia. A series of greenhouse and field experiments was carried out to assess the agronomic effectiveness of P fertilisers in particular local rock phosphates in typical cropping systems grown under lowland and upland conditions. Three pot and five field experiments were carried out using phosphate rock (PR) to improve crop production. The crops use were lowland and upland rice, soybean and mungbean, using a rotation of upland rice - soybean - mungbean.

In the lowland good fertile soils it was found that lower rates of P fertiliser can be applied to obtain yield increases and the PR was as effective as TSP.

In acid, P deficient upland soils, very high P rates were applied to study the residual effect in a crop rotation. This residual effect was observed in the third crop of the rotation. These soils have a very high phosphorus fixation capacity. Water was found the most important factor to increase crop yields in these upland areas. Overall, the experiments showed that the application of PR resulted in increase of crop yields expressed in dry weight of plant, grain, straw or stover. The combined use of PR and TSP enhanced the P uptake by crops. The use of ³²P had an added value in the determination of the agronomic effectiveness (AE) of PR. Where no ³²P was applied, the effectiveness of PR was determined by the RAE (relative agronomic effectiveness) indices.

Further experiments are needed to develop P fertiliser management practices for crops.
growing in the acid upland soils of Indonesia.

**Phosphorus Dynamics and Availability of Alternative Fertilisers Applied to Sustainable Agroecosystems in Southern China**

L.M. Xiong, Z.G. Zhou, G.L. Feng, and R.K. Lu

Acidic soils with high phosphorus-fixation capacity and relatively low phosphorus fertility are widely distributed in subtropical China. In an attempt to assess current phosphorus fertility and to evaluate the effectiveness of local rock phosphates on these soils, nearly 40 representative soils collected from the region were characterised by using $^{32}$P isotope exchange kinetics technique and chemical extraction procedures. Results indicated that the employed isotope kinetic model was suitable for evaluation of phosphorus fertility in moderately fertile soils yet it was less successful in predicting plant P uptake in soils with high P-fixing capacity. To overcome this difficulty, a new chemical extraction method consisting of sodium bicarbonate and ammonium fluoride was proposed to evaluate available P in these soils and the data generated with this method predicted better the plant P uptake amongst all methods compared. In pot experiments, the combined application of $^{32}$P labelled soluble P with local rock phosphate significantly enhanced plant growth and increased P uptake. One account for this positive interaction was attributed to the improved soil chemical properties by application of the low-grade rock phosphates as demonstrated in incubation studies. To increase the efficiency of rock phosphate-based fertilisers, plant factors that contributed to enhanced utilization of rock phosphates were also investigated. Significant exudation of organic acids in some plant species were found for the increased utilization of rock phosphates and Al as well as Fe associated phosphate forms in soils. Overall, it may be concluded from these results that an integrated approach taking into consideration both soil and plant factors should grant local rock phosphate-related phosphates as a successful alternative fertilisers for plants in acidic soils in southern China.
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