The
Soil–Plant
System

The Soil–Plant System

IN RELATION TO INORGANIC NUTRITION

AMERICAN INSTITUTE OF BIOLOGICAL SCIENCES
and
U. S. ATOMIC ENERGY COMMISSION

MONOGRAPH SERIES ON

RADIATION BIOLOGY

JOHN R. OLIVE, *Series Director*

AMERICAN INSTITUTE OF BIOLOGICAL SCIENCES

ADVISORY COMMITTEE

AUSTIN M. BRUES, *Argonne National Laboratory*
LEO K. BUSTAD, *Pacific Northwest Laboratory*
ERNEST C. POLLARD, *Pennsylvania State University*
CHARLES W. SHILLING, *Biological Science Communications Project*

MONOGRAPH TITLES AND AUTHORS

RADIATION, RADIOACTIVITY, AND INSECTS
    R. D. O'BRIEN, *Cornell University*
    L. S. WOLFE, *Montreal Neurological Institute*
RADIATION, ISOTOPES, AND BONES
    F. C. MCLEAN, *University of Chicago*
    A. M. BUDY, *University of Chicago*
RADIATION AND IMMUNE MECHANISMS
    W. H. TALIAFERRO, *Argonne National Laboratory*
    L. G. TALIAFERRO, *Argonne National Laboratory*
    B. N. JAROSLOW, *Argonne National Laboratory*
LIGHT: PHYSICAL AND BIOLOGICAL ACTION
    H. H. SELIGER, *Johns Hopkins University*
    W. D. MCELROY, *Johns Hopkins University*
MAMMALIAN RADIATION LETHALITY: A DISTURBANCE IN CELLULAR KINETICS
    V. P. BOND, *Brookhaven National Laboratory*
    T. M. FLIEDNER, *Brookhaven National Laboratory*
    J. O. ARCHAMBEAU, *Brookhaven National Laboratory*
IONIZING RADIATION: NEURAL FUNCTION AND BEHAVIOR
    D. J. KIMELDORF, *U. S. Naval Radiological Defense Laboratory*
    E. L. HUNT, *U. S. Naval Radiological Defense Laboratory*
TISSUE GRAFTING AND RADIATION
    H. S. MICKLEM, *Radiobiological Research Unit, Harwell*
    J. F. LOUTIT, *Radiobiological Research Unit, Harwell*
THE SOIL–PLANT SYSTEM IN RELATION TO INORGANIC NUTRITION
    M. FRIED, *International Atomic Energy Agency, Vienna*
    H. BROESHART, *International Atomic Energy Agency, Vienna*
TRITIUM–LABELED MOLECULES IN BIOLOGY AND MEDICINE
    L. E. FEINENDEGEN *Services de Biologie, Euratom*
RADIOISOTOPES IN THE HUMAN BODY: PHYSICAL AND BIOLOGICAL ASPECTS
    F. W. SPIERS, *University of Leeds*

The Soil–Plant System

IN RELATION TO INORGANIC NUTRITION

MAURICE FRIED
Joint FAO/IAEA Division of
Atomic Energy in Food and Agriculture
International Atomic Energy Agency
Vienna, Austria

HANS BROESHART
Section of Agriculture
International Atomic Energy Agency Laboratory
Vienna, Austria

Prepared under the direction of the American Institute
of Biological Sciences for the Division of Technical
Information, United States Atomic Energy Commission

1967

FOREWORD

This monograph is one in a series developed through the cooperative efforts of the American Institute of Biological Sciences and the U. S. Atomic Energy Commission's Division of Technical Information. The goal in this undertaking has been to direct attention to biologists' increasing utilization of radiation and radioisotopes. Their importance as tools for studying living systems cannot be overestimated. Indeed, their applications by biologists has an added significance, representing as it does the new, closer association between the physical and biological sciences.

The association places stringent demands on both disciplines: Each must seek to understand the methods, systems, and philosophies of the other science if radiation biology is to fulfill its promise of great contributions to our knowledge of both the normal and the abnormal organism. Hopefully, the information contained in each publication will guide students and scientists to areas where further research is indicated.

The American Institute of Biological Sciences is most pleased to have had a part in developing this Monograph Series.

JOHN R. OLIVE
Executive Director
American Institute of Biological Sciences

This page intentionally left blank

PREFACE

This work is intended as a monograph on the soil–plant system in
relation to the inorganic nutrition of plants. It can by no means be
considered a textbook, recording in detail all points that affect this
nutrition, e.g., very little coverage is given to such subjects as soil
aeration, hydroponics, organic soils, etc., nor are all the nutrient elements
discussed in detail in relation to each subject matter covered. It is
rather an attempt to view the dynamics of the process of ion uptake
in relation to those physical and chemical processes that must be con-
sidered both in understanding any observation made on the soil–plant
system and in predicting the results of any stress placed on the system;
such stress might, for example, be the removal of nutrients by the
plant or the addition of nutrients by fertilization.

The book is divided into two parts: the first includes primarily,
fundamental aspects of ion movement from the soil into and through
the soil solution, then into the plant root, and finally into the shoot;
the second includes the more practical aspects of the supply of nutrients
to plants grown in the soil–plant system and how it can best be supple-
mented. The emphasis throughout is on an understanding of both prob-
lems and the considerations necessary to solve them rather than on the
solution of any individual problem. References to the scientific literature
are extensive. The authors have drawn heavily from their own research
and experience, and, in addition, have attempted to present all other per-
tinent ideas together with their documentation. Nevertheless, this is not
presented as a literature review or recording of facts, but rather as an
over-all view as seen by the authors; finite conclusions are generally
drawn.

Although the publication was partially supported by funds from the
U. S. Atomic Energy Commission, no limitations were placed on the
authors as to emphasis or subject matter coverage relating to isotope or
radiation applications. Nevertheless, it should be pointed out that much of
the understanding and principles developed both on the more fundamental
and the applied aspects have involved isotope applications. This is
particularly evident in the subject matter coverage of solid-phase–soil-
solution relationships, movement of ions to the roots, into the roots
(active or passive), and translocation to the shoot, the mobility of nutri-

ents, laboratory, greenhouse, and field evaluation of soil nutrient supply and when, where, and what kind of fertilizer to apply.

The authors are greatly indebted to Professor H. Laudelout for his assistance in the preparation of the sections dealing with ion exchange and diffusion in soil systems. Thanks are also due to Professor G. H. Bolt for his help in the preparation of the section on cation exchange in soils. We are grateful to Professor R. A. Olson, Professor A. C. Caldwell, and Dr. R. E. Shapiro for their critical examination of the text and the many valuable suggestions made by them. Finally, we thank our wives for several years of patience; without their cooperation this manuscript could never have been completed.

October, 1967   MAURICE FRIED
                                                   HANS BROESHART

CONTENTS

PART I

Introduction

The soil–plant system together with energy from the sun is the primary source of food for land organisms and of food and fiber for man. The inorganic nutrition of plants grown in the soil–plant system is one of the main areas of effort where man has succeeded in appreciably affecting the quantity and quality of his food and fiber. Fertilizer consciousness by farmers and an enormous fertilizer industry are a result of the realization that man can exercise appreciable control over the amount and kind of agricultural produce yielded per unit area of land surface. In the United States alone the consumption of fertilizer nutrients in 1963 was 9,532,065 tons and the consumption is still increasing as shown in Table I.1.

TABLE I.1

TOTAL FERTILIZER NUTRIENT CONSUMPTION IN THE UNITED STATES
FROM JUNE 1960 TO JUNE 1963[a]

Year	N	P_2O_5	K_2O	Total
1960–1961	3,030,788	2,645,085	2,168,533	7,844,406
1961–1962	3,369,980	2,807,039	2,270,537	8,447,556
1962–1963	3,903,629	3,092,070	2,536,366	9,532,065

[a] Data given in short tons. From Scholl *et al.* (1964).

In other areas of the world outside of Western Europe and the Far East very little fertilizer is used, although the trend is also upward (Table I.2). Actually, the same lack of utilization occurs in the countries in the Far East outside of Japan and Taiwan.

This lack of utilization in most of the land areas of the world is not because fertilizer is not required, but primarily is a result of high cost and other economic factors, including transportation facilities and the difficulty of bringing the appropriate information to the attention of the farmers. In spite of the general over-all need for fertilizer, there are local areas where too much of a particular fertilizer nutrient is being utilized, resulting in economic loss or even reduced yields and quality of the product.

Only with knowledge and understanding of the soil-plant system can man hope to exercise the kind of control that will lead to the most efficient method of high production under the many varied environmental conditions of soil and climate. The present volume is, therefore, divided into two distinct parts. The first (Part II) deals with soil–plant relationships in their more basic aspects, including the information and considerations necessary to understand the system. The second (Part III) deals with the more practical aspects of supplying nutrients to plants, including the research information and considerations necessary for final evaluation of the system.

TABLE I.2
WORLD FERTILIZER CONSUMPTION BY REGIONS[a]

Region	1945/1946	1949/1950	1954/1955	1959/1960
Europe (excluding USSR)	3372	6388	9191	23,800
USSR	680	1025	1718	2340
North America	2672	4024	5887	7130
Latin America	154	225	481	840
Near East	48	133	206	250
Far East	86	1014	1748	2530
Africa	115	181	307	400
Oceania	373	507	722	840

[a] Data given in thousand metric tons of plant nutrients. From FAO (1962).

In both parts the emphasis of necessity is on those nutrient elements for which most of the research information exists. This means that nitrogen, phosphorus, and potassium may receive the most attention. Nevertheless, the principles indicated and research information needed apply to all nutrient elements. One nutrient element is no more essential than another; it is only the likelihood of deficiency in the practical situation that may be different.

Since the emphasis is primarily on the principles involved, the soil is generally treated as a relatively homogeneous system. The soil is not generally homogeneous, however, particularly in its gross aspects, and any practical applications of the principles involved must, of necessity, take account of the heterogeneity *in situ*.

PART II

Soil-Plant Relationships
in Ion Uptake

From the standpoint of practical agriculture, the inorganic nutrition of plants essentially concerns the uptake of nutrient ions from the soil into the plant system. In Chapters 1–4, the two components of this system, the soil and the plant, and their interrelationships are examined.

CHAPTER 1
Dynamics of the Soil-Plant System

As long as the plant is alive and its roots are in the soil, the soil-plant system with regard to inorganic nutrition is an open system in which nutrient ions are continuously removed from the system at one end (the solid phase) and accumulated at the other end (the plant), as shown in Eq. (1.1) where M is a nutrient ion.

$$\text{M(solid)} \rightleftharpoons \text{M(solution)} \rightleftharpoons \text{M(plant root)} \rightleftharpoons \text{M(plant top)} \quad (1.1)$$

The movement of ions from soil to plant top has been written as an equation not only to emphasize that all the processes taking place are physicochemical processes but also to suggest that knowledge of the concentrations of the reactants and the rate constants of each of the processes gives a rather complete description of the over-all process with the concomitant potential of process regulation.

Energy must be supplied to the system for the ion accumulation process to continue. In higher plants this energy comes from the absorption of quanta of light from the sun. To fully understand the process of inorganic nutrition in the soil–plant system, one must also understand this energy process (photosynthesis). For living higher plants, this energy

3

process is quite capable of changing the concentration of reactants and the magnitude of the rate constants (as might other factors in the environment), yet the physicochemical description of the over-all process will not normally change. No attempt is made to describe this over-all energy process which itself is the subject of many books and review articles (Bassham, 1957; Hill, 1958; Rabinowitch, 1945 and 1956; Terrien, 1957; Bladergroen, 1960; McElroy, 1961).

In an open system, such as that described in Eq. (1.1), the amount of ion accumulated in the plant top in a given (short) unit of time will equal the net loss of ion from the soil. When all the intermediate reactions are occurring at the same rate, none of the reactants are changing in concentration and $dMi/dt = 0$. The system is then considered to be in a steady state condition.

Ion uptake is a continuous dynamic process and all the reactions suggested and implied in Eq. (1.1) are going on all the time. The solution of the kinetic equation involving even two consecutive reactions is extremely complex. Reactions involving more than two steps lead to even greater difficulties. Practical solutions normally necessitate certain approximations (Dixon and Webb, 1958; Laidler, 1958). The steady state approximation is one of the most useful. The ion uptake process may be treated as a steady state system which reacts to changes in concentration of one of the reactants or of one of the rate constants by the necessary adjustments in all other reactions to result in a new steady state level. A few characteristics of a steady state system, with particular reference to determining the rate of the over-all reaction by the steady state approximation, are listed below.

(1) In a system at steady state all reactions are going on at the same rate, i.e., $dMi/dt = 0$.

(2) If the reverse step of a process in a steady state system is very rapid compared with the rate at which this intermediate undergoes reaction to the final product, then the preceding reactions are essentially at equilibrium.

(3) The steady state approximation includes a concept of the rate-limiting step, i.e., in a sequence of consecutive reactions the slowest reaction (or reactions) determines the rate of all the reactions.

(4) The steady state approximation is particularly good when the intermediate components are very reactive and, therefore, present at very small concentrations.

(5) In a chain of reactions in a steady state system no reaction after the first irreversible reaction plays any part in determining the over-all rate.

(6) A zero-order reaction in a chain of reactions determines the over-all rate.

(7) If in a chain of reactions an irreversible reaction occurs before a zero-order reaction, a steady state is impossible.

The individual reactions making up this continuum of the ultimate accumulation of an ion initially present in the solid phase can be studied individually, but their significance to the accumulation process cannot be evaluated without consideration of the rest of the reactions in the continuum. It is in this context that the approximation of the rate-limiting step is particularly useful.

Chapters 2 and 3 of Part II deal with the solid and liquid phase of the soil system, including their interrelationships, and with the plant system, including the plant root and translocation of nutrients. Chapter 4 of this more basic part will discuss the over-all process in relation to the accumulated information on the individual reactions.

CHAPTER 2

Characterization of the Soil System

The soil system consists of three phases: solid, liquid, and gaseous. The gaseous phase is important to the metabolism of the plant and interacts with the liquid phase. From the standpoint of nutrient supply to plants in the soil–plant system, however, only the solid and liquid phases will be considered. A discussion of the effect of soil air on plant nutrition is given by Currie (1962), Wiegand and Lemon (1958), Lemon and Wiegand (1962), Russell (1952), and Williamson (1964).

1. The Solid Phase

The solid phase is the reservoir of most plant nutrients and also contains the active surface which determines the concentration of ions in the soil solution. In Eq. (1.1) it has been referred to as M(solid), but M(solid) itself is a complex, since the soil consists of many distinct chemical species containing in their lattices or on their surfaces the same nutrient element.

The abundance in the lithosphere of elements of agricultural significance is given in Table 2.1. These totals represent the maximum reservoir from which nutrients can be drawn other than the contribution of the atmosphere and hydrosphere to the total H, O, N, and C and, to a lesser extent, S. The elements occur in distinct chemical forms and may be divided conveniently into primary minerals, secondary minerals, the uncombined oxides and salts, and organic matter. The oxides may be of primary or secondary origin, while the carbonates are always of secondary origin. The primary minerals (i.e., those minerals present in the original magma, the chemical composition of which remains unchanged) are, in general, confined to the coarser fractions of the soil that are greater than 2 μ. The secondary minerals (i.e., those minerals with a new chemical structure due to the action of the external environment on the primary minerals) are usually confined to the finer fractions that are smaller than 2 μ. There is, of course, some overlapping in sizes and the uncombined oxides and carbonates exist in both fractions, both as precipitates, particularly in the larger fractions, and as coatings on both primary and secondary minerals. The organic matter which may exist in all states of decomposition, in all size distributions, and both

6

TABLE 2.1

ABUNDANCE IN THE LITHOSPHERE OF SOME OF THE ELEMENTS
OF POSSIBLE AGRICULTURAL SIGNIFICANCE[a]

Atomic number	Element	Abundance (ppm)	Atomic number	Element	Abundance (ppm)
1	H	—[b]	23	V	150
5	B	10	25	Mn	1000
6	C	320	26	Fe	50,000
7	N	—[b]	27	Co	40
8	O	466,000	29	Cu	70
11	Na	28,300	30	Zn	80
12	Mg	20,900	33	As	5
13	Al	81,300	34	Se	0.09
14	Si	277,200	35	Br	2.5
15	P	1200	37	Rb	280
16	S	520	38	Sn	150
17	Cl	480	42	Mo	2.3
19	K	25,900	53	I	0.3
20	Ca	36,300	55	Cs	3.2
21	Sc	5	56	Ba	430

[a] From Goldschmidt (1954).
[b] Figure not given.

as entities and as coatings or even in chemical combinations with the mineral phase imposes further complexity upon the system.

Table 2.2 summarizes the elemental composition of mineral soils from the two climatic zones, tropical and temperate, as indicated from analysis in the literature. Soils containing as much as 50% free $CaCO_3$ may exist in dry areas. The chemical analysis of the mineral phase with

TABLE 2.2

ELEMENTAL COMPOSITION OF MINERAL SOILS FROM THE TROPICAL AND
TEMPERATE ZONES

Element expressed as oxide	Climatic zone		Element expressed as oxide	Climatic zone	
	Tropical (%)	Temperate (%)		Tropical (%)	Temperate (%)
SiO_2	3–30	60–95	CaO	0.05–0.5	0.3–2
Al_2O_3	10–40	2–20	MgO	0.1–3.0	0.05–1
Fe_2O_3	10–70	0.5–10	K_2O	0.01–1.0	0.1–4
MnO	0.1–1.5	0.005–0.5	Na_2O	0.01–0.5	0.1–2
TiO_2	0.5–15	0.3–2	P_2O_5	0.01–1.5	0.03–0.3

the $CaCO_3$ removed falls in the temperate range, as designated in Table 2.2.

1.1. PRIMARY MINERALS

A qualitative description of the primary mineral abundance by species is given in Table 2.3 and the chemical composition of representative primary minerals is given in Table 2.4.

Clearly, the nutrient elements Ca, Mg, K, Fe, and, to a lesser extent,

TABLE 2.3
PRIMARY MINERAL COMPOSITION OF IGNEOUS ROCKS[a]

Mineral	Chemical composition	Content (%)
Feldspar	Aluminosilicates of K, Na, Ca, Ba	60
Hornblende and augite	Aluminosilicates of Ca and Fe with other cations such as Na, Ca, Ti	20
Quartz	SiO_2	10
Mica	Aluminosilicates of K often combined with Fe and Mg	3
Hematite and magnetite	Fe_2O_3 and $Fe—Fe_2O_4$	3
Apatite	$Ca_5(PO_4)_3X$ (X = anion, e.g., F, Cl)	1

[a] From Vilenskii (1958).

TABLE 2.4
APPROXIMATE CHEMICAL COMPOSITION (%) OF PRINCIPAL PRIMARY
MINERALS IN SOILS[a]

Mineral	SiO_4	Al_2O_3	Fe_2O_3	FeO	TiO_2	CaO	MgO	K_2O	Na_2O	P_2O_5
Quartz	100	—	—	—	—	—	—	—	—	—
Orthoclase	62–66	18–20	—	—	—	0–3	—	9–15	9–4	—
Albite	61–70	19–26	—	—	—	0–9	—	0–4	6–11	—
Anorthite	40–45	28–37	—	—	—	10–20	—	0–2	0–5	—
Muscovite	44–46	34–37	0–2	0–4	—	—	0–3	8–11	0–2	—
Biotite	33–36	13–30	3–17	5–17	—	0–2	2–20	6–9	—	—
Hornblende	38–58	0–19	0–6	0–22	—	0–15	2–26	0–2	1–3	—
Augite	45–55	3–10	0–6	1–14	—	16–26	6–20	—	—	—
Olivine	35–43	—	0–3	5–34	—	—	27–51	—	—	—
Epidote	35–40	15–35	0–30	—	—	20–25	—	—	—	—
Apatite	—	—	—	—	—	54–55	—	—	—	40–42
Magnetite	—	—	69	31	—	—	—	—	—	—
Tourmaline	35–40	30–37	0–10	0–10	—	0–6	0–12	—	0–6	—
Rutile	—	—	—	—	100	—	—	—	—	—
Ilmenite	—	—	0–10	50	—	—	—	—	—	—

[a] From Bear (1953).