Field And Laboratory Research Manual For Integrated Soil Fertility Management In Kenya


MAY 2016
Per capita food production in Kenya has continued to decline in spite of the successful introduction of new crop varieties, associated fertilizer and pesticide packages coupled with excellent research outcomes. Natural disasters (increased incidences of floods and droughts); high incidences of pests and diseases and degradation of the soil resource base among others have been cited as the main reasons for the decline. Degradation of the soil resource base is directly linked to poor land management including land use without installation of appropriate erosion control measures and exportation of nutrients from farms through the plants and animal products without adequate replenishment of the removed nutrients. Additionally, harmonized soil fertility information collected by the Kenya Soil Health Consortium (KSHC) since 1925 (about 90 years) showed that most farmed soils were deficient in organic matter and are acidic. The decreased soil organic matter and widespread soil acidity is due to prolonged removal of crop residues, limited use of good quality organic manure and injudicious use of inorganic fertilizers. The rapid population increase, which currently stands at one million people per year, has put tremendous pressure on available arable land giving way to continuous cultivation, subdivision of agricultural land and migration from high potential areas to marginal ones. Thus the traditional way of maintaining soil fertility through shifting cultivation, application of suboptimal amounts of mineral fertilizers and/or manure and inclusion of grain legumes into the cropping systems is not sufficient to meet crop nutrients demands and ensure food security in the country. To deal with this problem both inorganic and organic fertilizers are essential and adequate quantities of the right types should be availed to a particular crop at the right crop stage following soil test recommendations.

A large body of research body to this effect is available such as the crop-soil and agro-ecological zone specific fertilizer recommendation developed by the Fertilizer Use Recommendation Project (1989 to 1994) and verified through the Fertilizer Extension Project (1994 to 1999), integration and optimization of organic and inorganic resources use and limiting nutrient trials carried out by Tropical Soil Biology and Fertility institute (1990’s to 2000’s) and within the last decade the International Plant Nutrition Institute and Alliance for a Green Revolution in Africa.

The results from these research efforts support combined use of organic and inorganic fertilizers popularly known as Integrated Soil Fertility Management (ISFM), which has proved to restore the soil resource capital base and significantly increase crop yields. ISFM is defined as the use of farming practices that involve the combined use of inorganic and organic inputs, improved seed and other planting materials combined with the knowledge on how to adapt these practices to local conditions so as to maximize the plant nutrient use efficiency while improving crop yields. All inputs need to be managed following sound farming principles.

This manual has been prepared by the Kenya Soil Health Consortium (KSHC) and features harmonized fertilizer use recommendations that were derived from ISFM research legacy data collected in Kenya. The legacy data covers research conducted between 1925 and 2015.
Acknowledgement

This harmonized fertilizer recommendation manual is the outcome of the joint effort of the Kenya Agricultural & Livestock Research Organization (KALRO) research staff in the Kenya Soil Health Consortium (KSHC) secretariat based at the National Agricultural Research Laboratories (NARL) Kabete; together with Dr. J. Mutegi of the International Plant Nutrition Institute (IPNI) who has been very instrumental in providing technical backstopping.

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Abbreviations and Acronyms

AGRA  Alliance for a Green Revolution in Africa
APVC  Agricultural Products Value Chains
IPNI  International Plant Nutrition Institute
ISFM  Integrated Soil Fertility Management
KALRO Kenya Agricultural & Livestock Research organization
KSHC  Kenya Soil Health Consortium
KUCC  Kenyatta University Conference Centre
NRM  Natural Resource Management
UoN  University of Nairobi
SFPNRP Soil Fertility & Plant Nutrition Research Programme
SEKU  South Eastern Kenya University
pH  Measure of soil acidity and alkalinity
N  Nitrogen
P  Phosphorus
K  Potassium
Ca  Calcium
Mg  Magnesium
S  Sulphur
Zn  Zinc
Cu  Copper
B  Boron
Fe  Iron
Mo  Molybdenum
Mn  Manganese
Cl  Chlorine
Co  Cobalt
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In Kenya research efforts have generated numerous Integrated Soil Fertility Management (ISFM) technologies with potential for increasing food production and rural incomes (Jama et al., 2000; Lekasi et al., 2001; TSBF, 2005; Salasya, 2005; Ojiem, 2006; AGRA, 2007; Misiko, 2007; Okalebo, et al., 2007; WAC, 2008; FAO, 2009; Rockstrom et al., 2009). However, these technologies have had limited impact on smallholder farmers' fields. The gap between research and application of ISFM guidelines is wide and evidenced by the low uptake and utilization of recommended ISFM technologies by smallholder farmers. Reasons for this unfortunate scenario include incoherent and conflicting recommendations for ISFM technologies because generators of ISFM technologies and innovations hardly collaborate and/or share their research outputs with each other or with end users. This also results in many inappropriate technology recommendations that confuse target farmers and lower technology adoption. These are the major reasons why farmers have been unable to realize the full benefits of the potential productivity gains possible from growing improved crop varieties, although adoption of these varieties is now widespread in the country (Rukandema, 1984; Omiti et al., 1999).

Although it is evident that appropriate use of ISFM can transform agriculture, the level of production with ISFM in Kenya has remained low. Part of the reason for low production ISFM can be traced to poor research. Successful ISFM research with a potential of increasing food production and incomes is best driven by appropriate field and laboratory research methods. In Kenya different laboratories use different methods to analyze for the same elements, often generating varying results for the same soil and plant samples. For example there are more than three methods for determination of soil and plant phosphorus levels used in different laboratories viz: Infra-red spectroscopy (IR), Bray II, Olsen, Mehlich I, II and III and the Truog methods. Recommendations based on the variable results from these methods are difficult to validate for reliability. Often this may lead to confusion and generation of wrong fertilizer recommendations leading to inappropriate use of farm inputs, soil acidification, low crop yields, low adoption, food insecurity and low household incomes. The Kenya Soil Health Consortium (KSHC) has developed this manual of field and laboratory methods through consultation with the major national, regional and international research and learning institutions to guide implementation of agricultural research in Kenya.

This protocol highlights among others; the process of research formulation, process of project implementation, field research methodology and approaches, plants-soil sampling and analysis, soil chemical analysis methods, fertilizer recommendation and use efficiency, and data management. The protocol is intended to act as a reference material and as a guide for future agricultural research and development in Kenya. This protocol is of great benefit to a wide range of stakeholders involved in agricultural research, agricultural extension, capacity building, and agricultural policy development.
THE PROCESS OF RESEARCH FORMULATION

Research is a systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions. It is divided into two general categories: (1) Basic research - It is an inquiry aimed at increasing scientific knowledge, and (2) Applied research – It is utilization of basic research results to solve real problems or to develop new processes, products, or techniques.

A research proposal - Research formulation starts with a proposal. It is an outline of the entire research process from beginning to end and may be used to request financing for the project. The outline of a research process is composed of the background to a problem or a gap or new materials, the justification to undertake the research, the aim and objectives of the research, methods to be used, activities to be undertaken to realize the aim and objectives of the research, expected outputs and the budget to implement the outline of the research process.

Good proposals quickly and easily answer the following questions:

• What do you want to do, how much will it cost and how much time will it take?
• How does the proposed project relate to institutional and donor’s interests (for funding solicitation projects)?
• What difference will the project make to the concerned parties, targeted stakeholders?
• What has already been done in the area of the proposed study?
• How do you plan to achieve the proposed objectives?
• How will the results be evaluated?
• Why it is you rather than somebody else who should do this project and who should be funded?

2.1 How to write a research proposal

Most beginning researchers and students do not fully understand what a research proposal means, nor do they understand its importance. An ill-conceived proposal dooms the project even if it somehow gets through the grant or thesis evaluation committee about the potential of the proponent.

A research proposal is intended to convince others that it is a worthwhile research project and that it has competent staff and the work-plan to complete it. Generally, a research proposal should contain all the key elements involved in the research process and include sufficient information for the readers to evaluate the proposed study.

The quality of one’s research proposal depends not only on the quality of the proposed project, but also on the quality of the writing. A good research idea may run the risk of rejection simply because the proposal is poorly written. Therefore, it pays if the writing is coherent, clear and compelling.

2.2 Parts of a proposal

Although there are variations in structures of proposals depending on the purposes of the proposal and the requirements of the sponsor, the following outline covers the primary components of a research proposal.

Title:

It should be concise and descriptive. For example, the phrase, “An investigation of . . .” could be omitted. Often titles are stated in terms of a functional relationship, because such titles clearly indicate the independent and dependent variables. However, if possible, think of an informative but catchy title. An effective title not only pricks the reviewer’s interest, but also predisposes him or her favorably towards the proposal.

Abstract or executive summary:

It is a brief summary of approximately 300 words. It should include the research question, the rationale for the study, the hypothesis (if any), the method and the main findings. Descriptions of the method may include the design, procedures, the sample and any instruments that will be used.

Introduction:

The introduction typically begins with a general
statement of the problem area, with a focus on a specific research problem, to be followed by the rationale or justification for the proposed study. The introduction generally covers the following elements:

1. Statement of the research problem, which is also the purpose of the study.
2. Provide the context and set the stage for the research question in such a way as to show the necessity and importance of the proposed research.
3. Present the rationale of the proposed study and clearly indicate why it is worth doing.
4. Briefly describe the major issues and sub-problems to be addressed by the research.
5. Identify the key independent and dependent variables of the experiment. Alternatively, specify the phenomenon needed for the study.
6. State the hypothesis or theory, if any. For exploratory or phenomenological research, one may not have any hypotheses.
7. Set the delimitation or boundaries of the proposed research in order to provide a clear focus.
8. Provide definitions of key concepts. (This is optional.)

**Literature Review:**

Sometimes the literature review is incorporated into the introduction section. However, most projects reviewers prefer a separate section, which allows a more thorough review of the literature.

The literature review serves several important functions:

1. Ensures that there is no “reinventing the wheel”.
2. Gives credits to those who have laid the groundwork for the research.
3. Demonstrates one’s knowledge of the research area.
4. Demonstrates one’s understanding of the theoretical and research issues related to the research question.
5. Indicates one’s ability to integrate and synthesize the existing literature.
6. Provides new theoretical insights or develops a new model as the conceptual framework for the research.
7. Convinces the reader that the proposed research will make a significant and substantial contribution to the literature (i.e., resolving an important theoretical issue or filling a major gap in the literature).

Most beginners researchers’ and students’ literature reviews suffer from the following problems:

- Lacking organization and structure
- Lacking focus, unity and coherence
- Being repetitive and verbose
- Failing to cite influential papers
- Failing to keep up with recent developments
- Failing to critically evaluate cited papers
- Citing irrelevant or trivial references
- Depending too much on secondary sources and internet

Scholarship and research competence will be questioned if any of the above applies to one’s proposal.

There are different ways to organize literature review. Make use of subheadings to bring order and coherence to the review. For example, having established the importance of the research area and its current state of development, one may devote several subsections on related issues as: theoretical framework, research instruments, cross-cultural and gender differences, etc. It is also helpful to keep in mind that one is telling a story to an audience. Try to tell it in a stimulating and engaging manner. Do not bore them, because it may lead to rejection of a worthy proposal.

**Methods:**

The Method section is very important because it tells the research evaluating committee how one has planned to tackle a research problem. It will provide the work plan and describe the activities necessary for the completion of the project.

The guiding principle for writing the Method section is that it should contain sufficient information for the reader to determine whether the methodology is sound and exhaustive. Some even argue that a good proposal should contain sufficient details for another qualified researcher to implement the study.

One needs to demonstrate knowledge of alternative methods and make the case that the approach is the most appropriate and most valid way to address the research problem at hand.

For qualitative research, since there are no well-established and widely accepted procedures in qualitative analysis, the method section needs to be more elaborate than what is required for quantitative research. More
importantly, the data collection process in qualitative research has a far greater impact on the results as compared to structured quantitative research.

For quantitative studies, the method section typically consists of the following sections:

1. Design - Is it a questionnaire study or a laboratory experiment? What kind of design does one choose?
2. Subjects or participants - Who will take part in the study? What kind of sampling procedure does one use?
3. Instruments - What kind of measuring instruments or questionnaires does one use? Why does one choose them? Are they valid and reliable?
4. Procedure - How does one plan to carry out the study? What activities are involved? How long does it take?

Results:
Obviously one does not have results at the proposal stage. However, one needs to have some idea about what kind of data to collect, and what statistical procedures will be used in order to answer the research question or test the hypothesis.

Discussion:
It is important to convince the reader of the potential impact of a proposed research. One needs to communicate a sense of enthusiasm and confidence without exaggerating the merits of a proposal. That is why one also needs to mention the limitations and weaknesses of the proposed research, which may be justified by time and financial constraints as well as by the early developmental stage of the research area.

Description of institutional resources
This section provides information about the resources available for the proposed research from the proposing institution. If possible it shows why the donor should select the proponent institution as opposed to others for this specific research. Some relevant points for this section include:

- The competence in the research area
- Abundance of experts in related areas may directly benefit the project
- Research facilities or instruments available for the project

Personnel
This section usually consist of two parts:

1. An explanation of the personnel arrangement
2. The biographical data for each of the main contributors to the project.

The explanation should specify how many persons, at what percentage of time and in what academic categories will be participating in the project. If the program is complex, and involves people from other institutions the organization of staff and the lines of responsibility should be made clear. Any student participation, paid or unpaid should be mentioned and the nature of proposed contribution detailed. If any person must be hired, for the project details and justification should be provided. It is crucial to engage the services of a biometrician in setting up an experiment to support randomization and replication of treatments which are crucial for analysis and interpretation of the results.

Logical frame (or a log frame)
A log frame (also known as a Project Framework) is a tool for planning and managing research development projects. It looks like a table (or framework) and aims to present information about the key components of a project in a clear, concise, logical and systematic way (table 2.2.1).

A log frame summarizes the following standard format:
- What the project intends to achieve?
- What activities will be carried out to achieve outputs and purpose of the project?
- The amount and type of resources required
- The potential problems/risk factors which could derail the success of the project
- How the progress and ultimate success of the project will be measured and verified?
Table 2.2.1 The structure of a logical frame

<table>
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<th>Problem Description</th>
<th>Objectively verifiable indicators of achievement</th>
<th>Source and means of verification</th>
<th>Assumptions</th>
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<td>Goal</td>
<td>What is the overall broader impact to which the action will contribute?</td>
<td>What are the key indicators related to the overall goal?</td>
<td>What are the external factors necessary to sustain objectives in the long term?</td>
</tr>
<tr>
<td>Purpose</td>
<td>What is the immediate development outcome at the end of the project?</td>
<td>Which indicators clearly show that the objective of the action has been achieved?</td>
<td>Which factors and conditions are necessary to achieve that objective? (external conditions)</td>
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<tr>
<td>Outputs</td>
<td>What are the specifically deliverable results envisaged to achieve the specific objective?</td>
<td>What are the indicators to measure whether and to what extent the action achieves the expected results?</td>
<td>What are the external conditions that must be met to obtain the expected results on schedule?</td>
</tr>
<tr>
<td>Activities</td>
<td>What are the key activities to be carried out and in what sequence in order to produce the expected results?</td>
<td><strong>Means:</strong> What are the means required to implement these activities, e.g. personnel, equipment, supplies, etc?</td>
<td><strong>Costs</strong> What are the action costs?</td>
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3.0 PROCESS OF PROJECT IMPLEMENTATION

Definition: - Is the putting into practice what was proposed in the project document i.e. executing the project intentions.

Project Implementation Involves:
• Project activation, and project operation

Project activation: Means making arrangements to have the project started. It involves planning, coordination and allocation of resources to make the project operational.

Project operation: This is practical management of a project. Here, project inputs are transformed into outputs or project activities are executed to achieve immediate objectives.

3.1 Approaches to Project Implementation

Top-down approach
Implementation is mainly done by the Principal Investigator (PI), research team or agencies from outside the community with limited involvement of the beneficiaries.

Bottom-up approach
Beneficiaries implement the project. Outside agencies may provide the financial resources and technical assistance.

Collaborative participatory approach
Both Top-down and bottom-up approaches to project implementation are applied in the process.

3.2 Project Implementation Plan (PIP)
If the PIP is not prepared during the project formulation and writing process, and embodied in the project documents, it is prepared and carried out at the project activation stage.

Project implementation plan includes:
The project implementation schedule
This is concerned with:
• What activities can produce expected project outputs?
• What is the sequence of these activities?
• What is the time frame for these activities?
• Who will be responsible for carrying out each activity?

The following methods may be used to answer the above questions:
• Gantt chart
• Critical Path Method (CPM) or Net work analysis
• Project Evaluation and Review Techniques (PERT)
• Simple formats

The Gantt Chart (also referred to as the progress chart):
Also Called: Milestones Chart, Project Bar Chart, Activity Chart, Activity Network Diagram
• It is a chart showing the timing of project activities using horizontal bars.
• It is one of the techniques of project scheduling, which depicts the frequency of activities and determines the period of time for implementation.

How to determine a Gantt chart
• Determine the parts or implementation phases of the project and the sequence in which the associated activities shall be carried out
• Then estimate the amount of time required for each activity
• List the activities that can be carried out at the same time and identify those to be carried out sequentially

How to construct a Gantt chart (Fig. 3.2.1)
• Time represented on the horizontal axis, and activities on the vertical axis.
• Bars are entered to indicate the time period allocated for each activity and the state of progress at any particular point in time.

The role of the implementing agency
• The specific responsibilities of the key staff during project implementation and monitoring are outlined.

Beneficiary participation
• The involvement of the beneficiaries in planning and implementation and what is expected of them is spelt out.

Organizational structure and staffing
Here the following are sought:
• Project structure for purposes of management
Qualifications and skills for the staff
Job descriptions and specifications for the staff
Technical assistance if needed

Financial management
This looks at funds management, accounting period, financial reports and statements and how often they will be made?

Reporting system
This looks at who will be reporting to whom and how often. There is need to design standard reporting formats.

Sustainability
• The concept of sustainability is based on belief that a project should result in benefits that have lasting effect. The project should be sustained beyond the life of funding - especially if it is a grant.
• The project should not exhaust the available resources like raw materials and labor.

Time control and remedial action
• Time taken to implement project activities is one measure of successfulness of supervision or monitoring of project implementation.
• Supervisor pays particular attention to time control measures, time scheduling and its supervision, time extension and postponement, damages for non-completion and defect or warranty period.

Supervision of implementation of project schedule
• This involves a set of checks and balances to ensure that the schedule is being adhered to.
• To ensure that the time schedule is being adhered to, the project activity time listing can be of great importance.

3.3 Factors Affecting Project Implementation
Factors that Lead to Success of Projects
• Simplicity of Design
• Careful preparation
• Good management
• Involvement of beneficiaries/community
• Political Commitment

Factors and Problems that Lead to Failure of Projects
• Financial Problems
• Management problems
• Technical problems
• Political problems

Other Typical Implementation Problems
• Poor scheduling of projects leading to delays in implementation.
• Misallocation of funds
• Delay and sometimes lack of counterpart funding
• Lack of accountability and transparency
• Bureaucracy in decision-making.
• Selfishness/nepotism/favoritism by some project managers.
• Weak monitoring systems
• Natural calamities like drought, earthquakes, landslides, and hailstorms.
• Policy changes
• Migration of beneficiaries
• Lack of team work
• Lack of incentives for implementers.

3.4 Project Exit strategy for sustainability of project output
The term exit strategy refers to project planning for sustaining outputs and deliverables after completion of the funding phase. Increasingly, funders may ask about exit strategy as part of the application process and prefer to support those projects which have a realistic plan about how they might continue their activity after the grant ends. An exit strategy should be planned at the start of the project.

There are two main ways to approach an exit strategy.
The project can either find:
• An alternative way to continue the activities and use of project outputs
• An alternative means to fund the activities
• Commercialization of the project outputs to make the project self sustaining
• A combination of all the above approaches.
A number of factors can contribute to projects being sustainable. These include:
• Good project planning
• Strong relationships with partners, communities and policy makers
• Involving potential continuation funders at an early stage
• Embedding private sector and commercializing project output
• Embedding learning and development skills in the project
• Support for staff continuity

The budget
Donors customarily specify how budgets should be presented and what costs are allowable. The budget delineates the costs to be met by the funding source including personnel, non-personnel, administrative and overhead expenses. The budget also specifies items paid for by other funding sources. It also includes justification for requested expenditures. A summary of components of the proposal is presented in fig 3.4.1.
Fig 3.4.1 Research proposal flow chart
Background

Agronomic research makes use of established field and laboratory procedures or measurements. These measurements entail estimating the nutrients in the soils that are necessary for most appropriate crop growth. Plants require at least 16 elements for normal growth and for completion of their life cycle. Those used in the largest amounts, carbon (C), hydrogen (H) and oxygen (O), are non-mineral elements supplied by air and water. The other 13 elements are taken up by plants only in mineral form from the soil or leaf and must be added as fertilizers. Plants need relatively large amounts of nitrogen (N), phosphorus (P), and potassium (K). These nutrients are referred to as primary nutrients, and are the ones most frequently supplied to plants in fertilizers. The three secondary elements viz: calcium (Ca), magnesium (Mg), and sulphur (S), are required in smaller amounts than the primary nutrients. Calcium and Mg are usually supplied with liming materials and S with fertilizer materials. The micronutrients consist of seven essential elements: boron (Bo), copper (Cu), chlorine (Cl), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). These elements occur in very small amounts in both soils and plants, but their role is equally as important as the primary or secondary nutrients. A deficiency of one or more of the micronutrients can lead to severe depression in growth, yield, and crop quality. Some soils do not contain sufficient amounts of these nutrients to meet the plant’s requirements for rapid growth and good production. In such cases, supplemental micronutrient applications in the form of solutions fertilizers or foliar sprays must be made. Soils will be tested to assess their fertility status (levels of plant nutrients in them). Detailed information on the nutrient deficiencies, toxicities and management factors is presented in table 4.0.1

An element is termed as essential if:

- It is impossible to complete the plant lifecycle without the element.
- The deficiency is specific to that particular element.

- The element is directly involved in the nutrition of the plant for example as an organic constituent or as an enzyme activator.

Reason why micro-nutrients are gaining increasing importance in agriculture

- The shift towards intensive farming systems to achieve high yields necessitates higher nutrient uptake.
- Continuous mining of nutrients without adequate replenishment.
- Usage of high analysis fertilizers that do not carry a significant amount of trace elements
- Better diagnostic tools to detect micronutrient deficiencies.
- Advancement in human nutrition revealing that you are what you eat and that crops grown in nutrient deficient soils do not provide sufficient nutrients to human and animal diets (link to soil health and human/animal health).

The concept of hidden hunger:

This is where plant may be nutrient-deficient without showing visual deficient symptoms

Deficiency range: Plant experience deficiency which is manifested by reduced growth and expression of deficiency symptoms

Sufficiency range: plants grow well and further supply of the nutrient does not match with corresponding increase in growth although the concentration of the nutrient may continue to increase in the plant tissue.

Toxicity range: this is where the plant has taken up too much nutrient until it is detrimental to growth by causing adverse physiological reactions to the plant

Table 4.0.1 below shows the essential nutrients both macro and micro, their functions in plants, non-visual and visual deficiency and toxicity symptoms.
<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Functions</th>
<th>Deficiency symptoms</th>
<th>Visual Deficiency symptoms</th>
<th>Toxicity symptoms</th>
<th>Management factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>Protein formation, photosynthesis.</td>
<td>Yellowing of lower leaves</td>
<td></td>
<td>Plants are stunted, deep green in colour, and secondary shoot development is poor</td>
<td>- Reduce leaching losses.  - Increase biological N-fixation (BNF).  - Maintain or increase SOM.  - Use N fertilizers efficiently.  - Return crop residues to the field.</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>Energy storage/transfer, root growth, crop maturity, straw strength, disease resistance.</td>
<td>Formation of purple colour on lower leaves</td>
<td>Leaf edges of the upper leaves brown or scotched Death of growing points of upper leaves</td>
<td></td>
<td>- Add P to soil as fertilizer.  - Maintain SOM.  - Increase P-use efficiency by applying P fertilizers together with readily decomposable organic residues and animal manures.</td>
</tr>
<tr>
<td>Potassium</td>
<td>Plant turgor pressure maintenance, accumulation and transport of the products of plant metabolism, crop disease resistance.</td>
<td>Browning of leaf edges of the lower leaves</td>
<td>Yellowing between leaf veins of lower leaves</td>
<td></td>
<td>- Reduce leaching losses.  - Return crop residues and animal manure from livestock fed with fodder taken from the field.  - Add K fertilizers to the soil.</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Photosynthesis</td>
<td>Yellowing between leaf veins of lower leaves</td>
<td></td>
<td>Brown spots on leaf veins. Necrosis starting at the tips and margins. Leaf crinkling.</td>
<td>- Return crop residues and animal manure from livestock fed with fodder taken from the field.  - Add Mg fertilizer or dolomitic lime to the soil.</td>
</tr>
<tr>
<td>Calcium</td>
<td>Cell growth and walls, required by groundnut for nut development.</td>
<td>Leaf edges of the upper leaves brown or scotched Death of growing points of upper leaves</td>
<td>Toxicity symptoms have not been reported for crops under field conditions</td>
<td></td>
<td>- Return crop residues and animal manure from livestock fed with fodder taken from the field.  - Add Ca fertilizers or lime to the soil.</td>
</tr>
<tr>
<td>Iron</td>
<td>Photosynthesis and respiration. Participates in oxidation reduction reaction of nitrates, sulphates and nitrogen fixation</td>
<td>Yellowing of upper leaves between leaf veins</td>
<td>Bronzing and purple discoloration of leaves in other crops</td>
<td></td>
<td>- Return crop residues.  - Maintain SOM.  - Do not burn crop residues.</td>
</tr>
<tr>
<td>Manganese</td>
<td>Is a component of enzymes and is also involved in photosynthesis and root growth. It is involved in nitrogen metabolism and assimilation.</td>
<td>Yellowing of upper leaves between leaf veins</td>
<td>Chlorosis, or blotchy leaf tissue due to insufficient chlorophyll synthesis. Growth rate will slow and vigour will decline. Leaf edges and tips also become chlorotic, which leads to the death of the leaf. Young leaves may become cupped and crinkled.</td>
<td>Add organic matter High amounts of copper, iron, and zinc may induce manganese deficiency. Over-liming soils can cause Mn deficiencies. <strong>Manganese sulfate</strong>: Contains 26-28% Mn; May be applied as a foliar spray and/or directly to the soil in a band application <strong>Manganese chelate</strong> (EDTA): Contains 5-12%; Not recommended as a broadcast</td>
<td></td>
</tr>
<tr>
<td>Nutrient</td>
<td>Functions</td>
<td>Deficiency symptoms</td>
<td>Visual Deficiency symptoms</td>
<td>Toxicity symptoms</td>
<td>Management factors</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>---------------------</td>
<td>---------------------------</td>
<td>-------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td><strong>Copper</strong></td>
<td>Chlorophyll and seed formation, protein synthesis. Improves fertility. Good cob development. Improves yield. Brings harvest date forward.</td>
<td>Yellowing of upper leaves between leaf veins. The youngest leaves show yellow interveinal discoloration as they come out of the whorl. Mainly the basal part of the leaf is uniformly yellow-green.</td>
<td><img src="image1" alt="Copper Deficiency symptoms" /></td>
<td>Chlorosis and necrosis of older leaves. Inhibition of root elongation.</td>
<td>Foliar applications of Copper (Cu) can be an effective way to correct Cu deficiencies. The stage of growth at the time of application has a major influence on the effectiveness of the treatment.</td>
</tr>
</tbody>
</table>
| **Boron** | Development/growth of new cells. | Death of growing points of upper leaves. | ![Boron Deficiency symptoms](image2) | Chlorosis and necrosis of leaf tips and margins. | There is currently no practical treatment option for B deficiency. Where possible:  
- Apply B in soluble forms (borax) for rapid treatment (0.5–3 kg B/ha). Broadcast and incorporate it before planting. It can also be top dressed, or used as foliar spray during vegetative growth. Do not mix borax and fertilizer borates with ammonium fertilizers. |
| **Sulphur** | Synthesis of amino acids. Production of chlorophyll and utilization of other essential nutrients. Ranks at par with nitrogen for optimizing crop yield. Crops that have a high nitrogen requirement must have adequate sulphur to optimize nitrogen utilization. | Yellowing of upper leaves | ![Sulphur Deficiency symptoms](image3) | Leaf size will be reduced and overall growth will be stunted. Leaves yellowing or scorched at edges. | There is currently no practical field management option for S deficiency. Where possible,  
- Apply S to the field by using S-containing fertilizers.  
- Incorporate straw/Stover instead of completely removing or burning it.  
- Improve soil management to enhance S uptake by maintaining sufficient percolation (~5 mm per day) or by carrying out dry tillage after harvesting. |
| **Chlorine** | Stimulates photosynthesis, osmoregulation and disease suppression. Increases cell osmotic pressure and water content of the plant tissue. | Chlorosis of younger leaves and wilting of the plant. Deficiency seldom occurs because chlorine is found in atmosphere and water. | ![Chlorine Deficiency symptoms](image4) | Premature yellowing of young lower leaves, burning of leaf margins and tips, plants will easily wilt leaf abscission will occur primarily for woody plants. | Some Common Fertilizer Products Containing Chloride:  
- Sodium Chloride (NaCl) contains 61% chlorine.  
- Potassium Chloride (KCl) contains 47% chlorine and Calcium Chloride (CaCl2) contains 64% chlorine. |
| **Molybdenum** | Nitrogen fixation and assimilation. Necessary for nitrate reductase and nitorgenase. | Older and middle leaves become chlorotic and the leaf margins roll towards. Deficient plant are stunted and flower formation may be restricted. Mo deficiency can be common in N-fixing legumes. | ![Molybdenum Deficiency symptoms](image5) | Most plants are quite tolerant to high Mo concentrations. In the greenhouse studies tomato leaves turned golden yellow. Animals fed on high Mo may need supplemental Cu to counteract the Mo effect. | Molybdenum compounds used for crops include molybdenum trioxide, sodium molybate and ammonium molybdate.  
Molybdenum trioxide (also called molybdic oxide) contains 66 per cent molybdenum.  
Ammonium molybdate contains 54 per cent molybdenum.  
Sodium molybdate is usually sold in a form containing 39 per cent molybdenum. It is sold as fine crystals which dissolve readily in cold water and this material is undoubtedly the most convenient for the preparation of solutions to be used for spraying. |
| **Zinc** | Aids plant growth hormones and enzyme systems. Necessary for chlorophyll, carbohydrate, and starch formation. Aids in seed formation and maturation. | Intervenal chlorosis occurs on younger leaves similar to Fe deficiency however, Zn deficiency is more defined appearing as banding at the basal part of the leaf whereas Fe deficiency result in. | ![Zinc Deficiency symptoms](image6) | Excessive Zn levels may occur on extremely acidic soils (<pH 5). A general guide for Zn concentration in mature leaf tissue is as follow: deficient <20 ppm, sufficient 25-150 ppm, | There are many fertilizer sources of zinc effective in correcting zinc deficiencies. These sources can be grouped as:  
Soluble inorganic products, such as zinc sulfate (35% Zn), and zinc ammonium complex (10% Zn).  
Insoluble inorganic products such as zinc oxide (70-80% Zn) and zinc carbonate.  
Organic chelates such as ZnEDTA (9-14% Zn), ZnHEDTA, and Organic non-chelates (natural organic complexes). |
The optimum rate
The optimum rate is one that will supply nutrients slightly above the critical value, where further yield response to additional nutrient supply is not expected. The economic loss of supplying nutrients below that critical level is usually greater than the cost of supplying nutrients at a rate marginally above the critical level. Higher rates of some nutrients can lead to luxury consumption and, in extreme cases, to toxicity to the growing crop. Toxic application rates from fertilizers are not usually observed due to fertilizer cost. These higher levels should be avoided because they result in unnecessary fertilizer costs, potential loss of yield, and increased risk of nutrient losses to the environment. The right rate should take into account all sources of nutrients, including soil supply (estimated using soil tests or omission plots1), manure and other organic sources, crop residues, biological N fixation, irrigation water and atmospheric deposition. Figure 4.0.1 illustrates the various sufficiency ranges for nutrients applied to a given crop.

Effects of not applying the right rate of nutrients (IFA World Fertilizer Use Manual, 1992)

4.1 How to determine the amount of nutrients required by crops
Different crops require different amounts of nutrients for healthy growth and maturity. The quantity of nutrients required also depends largely on the crop yield targeted. Matching nutrient supply with plant nutrient demand is required to select the right fertilizer rate. Most of the nutrients taken up by the crop will be removed from the field in the harvested portion of the crop, while the remainder will be recycled back into the system as crop residue. In situations where crop residues are removed to feed livestock, for fuel, or burnt, almost all nutrients taken up by the crop are removed from the field. The total amount of nutrients required by a specific crop and yield level can be estimated by multiplying the expected yield for that crop by the amounts of nutrients taken for each tone of yield. Estimates of nutrients removed for low, medium and
Table 4.1.1: Nutrients removed by crops at different yield levels

<table>
<thead>
<tr>
<th>Crop</th>
<th>Grain yield t/ha</th>
<th>N</th>
<th>P2O5</th>
<th>K2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>1</td>
<td>24</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>48</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>96</td>
<td>48</td>
<td>72</td>
</tr>
<tr>
<td>Rice</td>
<td>2</td>
<td>32</td>
<td>17</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>64</td>
<td>34</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>96</td>
<td>51</td>
<td>150</td>
</tr>
<tr>
<td>Wheat</td>
<td>1</td>
<td>24</td>
<td>9</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>48</td>
<td>18</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>96</td>
<td>36</td>
<td>88</td>
</tr>
<tr>
<td>Sorghum/Millet</td>
<td>1</td>
<td>20</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>40</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>80</td>
<td>48</td>
<td>120</td>
</tr>
<tr>
<td>Soybean</td>
<td>1</td>
<td>80</td>
<td>18</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>160</td>
<td>36</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>320</td>
<td>72</td>
<td>160</td>
</tr>
<tr>
<td>Beans</td>
<td>1</td>
<td>65</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>130</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>260</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>Groundnuts</td>
<td>1</td>
<td>70</td>
<td>12</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>140</td>
<td>24</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>280</td>
<td>48</td>
<td>112</td>
</tr>
</tbody>
</table>

4.2 Differentiating deficiency symptoms from effect of diseases

Solving the problem may be fairly simple if it is diagnosed correctly. When a plant shows symptoms, check first to see if a disease organism is present. When an insect causes a plant problem, the insects themselves (or their eggs or other signs) are often visible. If a fungus causes plant disease, there are generally signs such as the fuzzy threads (hyphae) that they produce or other clear indications that can be traced. Getting rid of these organisms or restoring good growing conditions may be the answer. Environmental changes may cause plant problems that are similar to nutrient deficiencies or plant disease. Determine whether the plant is getting enough or too much sun; whether it is receiving correct moisture; and whether the temperatures are acceptable for its growth. A shade-loving plant will get burned in full sun, and a plant designed for full sun will not thrive with limited light. Likewise, when a plant is suffering from a deficiency in one essential nutrient or another, there are usually consistent telltale indications unique for each nutrient, but these may appear much like symptoms of pests or environmental conditions.

Nutrient deficiencies are often related to other problems.

- Is the plant getting enough water? Too much?
  Check the soil moisture, and make sure that there is sufficient drainage. Improper watering, too much or too little, can prevent the plant from obtaining nutrients.
- Is the soil too acid or too alkaline? Nutrients are more or less available in acidic or alkaline soils.
  - This is measured as pH, on a scale of 1 (very acid, e.g. concentrated sulfuric acid) to 14 (very alkaline e.g. lye). Neutral pH is 7.
  - Many plants grow best in a pH range of 5.5 – 7.5
Soils in the desert tend to have quite a high pH, 8.5 or higher, which inhibits normal plant growth. Soils in areas that receive much rain are usually quite acidic.

Iron, manganese and zinc are three essential elements that become inaccessible above pH 7.8, hence deficiency of one of these minerals is common in the desert.

Is the soil very cool?

Certain nutrients are inaccessible when soils are cool, but the definition of “too cool” varies with the plant. For instance, a cactus will have difficulty taking up nutrients from soils at a temperature that might be perfectly fine for a pine.

### Table 4.2.1 Relative response of selected crops to micronutrient fertilizers

<table>
<thead>
<tr>
<th>Crop</th>
<th>Mn</th>
<th>B</th>
<th>Cu</th>
<th>Zn</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Sorghum</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Wheat</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Barley</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Common Bean</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Garden Pea</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Soybean</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Potato</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Tomato</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Broccoli</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrot</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Onion</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Cabbage</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Spinach</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Snap Bean</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Celery</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cucumber</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Pepper</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>

1. Highly responsive crops will often respond to micronutrient fertilizer additions if the micronutrient concentration in the soil is low. Medium responsive crops are less likely to respond, and low responsive crops do not usually respond to fertilizer additions even at the lowest soil micronutrient levels.

### 4.3 Nutrient/elemental toxicities

The toxicities most commonly found in food crops are those of aluminium, manganese, and iron. Aluminium and manganese toxicities are most common in acid soils, whereas iron toxicity occurs in flooded rice under reduced soil conditions. When excess Al, Mn and Fe are present in the growth medium, they may inhibit the uptake, the transport, and the utilization of many other nutrients and induce nutritional deficiency. Increase in Al concentration in growth medium inhibits the concentration of N, P, K, Ca, Mg, Zn, Fe, Mn and Cu. High Fe concentrations in growth medium reduces uptake of P, K, N, Mn and Zn hence inducing their deficiencies. Table 5.1.1 presents common nutrient and elemental toxicities in important soil groups.
Table 4.3.1 Element deficiencies and toxicities associated with major soil groups.

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Soil Group</th>
<th>Element</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andisols (Andepts)</td>
<td>Andosol</td>
<td>P, Ca, Mg, B, Mo</td>
<td>Al</td>
</tr>
<tr>
<td>Ultisols</td>
<td>Acrisol</td>
<td>N, P, Ca</td>
<td>Al, Mn, Fe</td>
</tr>
<tr>
<td>Ultisols/Alfisols</td>
<td>Nitosol</td>
<td>P</td>
<td>Mn</td>
</tr>
<tr>
<td>Spodosols (Podsols)</td>
<td>Podzol</td>
<td>N, P, K, Ca, micronutrients</td>
<td>Al</td>
</tr>
<tr>
<td>Oxisols</td>
<td>Ferralsol</td>
<td>P, Ca, Mg, Mo</td>
<td>Al, Mn, Fe</td>
</tr>
<tr>
<td>Histosols</td>
<td>Histosol</td>
<td>Si, Cu</td>
<td></td>
</tr>
<tr>
<td>Entisols (Psamments)</td>
<td>Arenosol</td>
<td>K, Zn, Fe, Cu, Mn</td>
<td></td>
</tr>
<tr>
<td>Entisols (Fluvents)</td>
<td>Fluvisol</td>
<td></td>
<td>Al, Mn, Fe</td>
</tr>
<tr>
<td>Mollisols (Aqu), Inceptisols, Entisols etc (poorly drained)</td>
<td>Gleysol</td>
<td>Mn</td>
<td>Fe, Mo</td>
</tr>
<tr>
<td>Mollisols (Borolls)</td>
<td>Chernozem</td>
<td>Zn, Mn, Fe</td>
<td></td>
</tr>
<tr>
<td>Mollisols (Ustolls)</td>
<td>Kastanozem</td>
<td>K, P, Mn, Cu, Zn</td>
<td>Na</td>
</tr>
<tr>
<td>Mollisols (Aridis) (Udolls)</td>
<td>Phaeozem</td>
<td></td>
<td>Mo</td>
</tr>
<tr>
<td>Mollisols (Rendolls) (shallow)</td>
<td>Rendzina</td>
<td>P, Zn, Fe, Mn</td>
<td></td>
</tr>
<tr>
<td>Vertisols</td>
<td>Vertisol</td>
<td>N, P, Fe</td>
<td>S</td>
</tr>
<tr>
<td>Aridisols</td>
<td>Xerosol</td>
<td>Mg, K, P, Fe, Zn</td>
<td>Na</td>
</tr>
<tr>
<td>Aridisols/Arid Entisols</td>
<td>Yermosol</td>
<td>Mg, K, P, Fe, Zn, Co, I</td>
<td>Na, Se</td>
</tr>
<tr>
<td>Alfisols/Ultisols (Albic) (poorly drained)</td>
<td>Planosol</td>
<td>Most nutrients</td>
<td>Al</td>
</tr>
<tr>
<td>Alfisols/Aridisols/Mollisols (Natric) (high alkali)</td>
<td>Solonetz</td>
<td>K, N, P, Zn, Cu, Mn, Fe</td>
<td>Na</td>
</tr>
<tr>
<td>Aridisols (high salt)</td>
<td>Solonchak</td>
<td></td>
<td>B, Na, Cl</td>
</tr>
</tbody>
</table>
### 4.4 Nutrient sources to correct soil nutrient deficiencies

It is not enough to diagnose soil nutrient deficiencies. It is paramount to consider the materials and the right conditions required to correct them. The following are materials and conditions necessary for correcting soil nutrient deficiencies (Table 4.4.1):

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Sources</th>
<th>Recommendations for most Kenyan soils</th>
<th>Important points to note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>Urea, CAN, AS, DAP, NPK, Mavuno, Farmyard manure, compost, green manure, BNF</td>
<td>Inorganic: 20-60 kg N/ha for annual crops Organic: 2-5 t/ha BNF (inoculant):10g/kg of seed</td>
<td>• Split applied at planting and 2-4 weeks after germination. BNF is used in relay and intercropping systems</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>DAP, TSP, SSP, NPK, Mavuno, Rock phosphate, Farmyard manure, compost, green manure,</td>
<td>Inorganic: 20-40 kg P/ha Organic: 2-5 t/ha</td>
<td>• Applied during planting to enhance root system development • Soils with inherent pH values between 6 and 7.5 are ideal for P availability (Crop response to P application) while pH values below 5.5 and between 7.5 and 8.5 limits P availability to crops due to P fixation by Aluminium, Iron or Calcium which are usually associated with the soil parent materials. • P availability is controlled by three primary factors: Soil pH, amount of organic matter and proper placement of P fertilizer</td>
</tr>
<tr>
<td>Potassium</td>
<td>Muriate of potash, NPK, Potassium sulphate, potassium nitrate, Mavuno, Farmyard manure, compost, green manure</td>
<td>Inorganic: 10-30 kg K/ha Organic:2-5 t/ha</td>
<td>• Applied at planting • When K is limiting it limits the availability of N and P • Cation exchange capacity is the key determinant of the amount of K available for plant uptake. • It is difficult to build soil potassium levels especially in soils with high percentage clay. In clay soils K is bound becoming unavailable for plant uptake. • Plants can take up more K without increase in crop yield (luxury consumption). • Therefore it wise to apply only the needed amount to meet the yield goal for the season. • High rates of potassium enable efficient use of N and P leading to better early vegetative growth and higher grain/straw growth</td>
</tr>
<tr>
<td>Sulphur</td>
<td>SSP, Potassium sulphate, Mavuno, Farmyard manure, compost, green manure, atmospheric deposition, gypsum, ammonium sulphate, Kieserite, Thiosulphate</td>
<td>Inorganic: 5-10 kg S/ha Organic: 2-5 t/ha</td>
<td>• Applied at planting • Elemental sulphur is applied well in advance crop demand since a lag period of bacterial oxidation and conversion to sulphate is involved. • It may be subject to leaching losses similar to nitrate • There are no adverse environmental impacts associated with typical concentrations of sulphate in water.</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Dolomitic (MgCO₃,CaCO₃) lime, magesite (MgCO₃), magnesium sulphate (MgSO₄·7H₂O), Kieserite (MgSO₄·H₂O), Kainite (MgSO₄·KCl·3H₂O), Magnesium Chloride (MgCl₂), Magnesium Nitrate (Mg(NO₃)₂·6H₂O), Magnesium Oxide MgO</td>
<td>Inorganic: When Mg level in the soil is &lt;20 g/kg, soil pH &lt; 6.0, apply dolomitic lime. When Mg level in the soil is &lt;20 g/kg, soil pH &gt; 6.0, apply magnesium sulphate Application rate at 10-20 kg Mg/ha Organic: 2-5 t/ha</td>
<td>• Applied at planting • Magnesium deficiencies are common in low pH soils, and sandy soils where Al dominates cation exchange sites. High exchangeable concentration can have an adverse effect on Mg availability for plants. The competition between these two cation for root uptake is the primary cause. • The pathways for Mg loss include crop removal, leaching losses, erosional loss</td>
</tr>
</tbody>
</table>
### Calculating fertilizer requirement from fertilizer recommendations

The amount of fertilizer to be applied per hectare or on a given field is determined through the amount of nutrients needed and the types and grades of fertilizers available. Usually mineral fertilizers are delivered in 50 kg bags. Therefore, the farmer has to know the quantity of nutrients contained in a 50 kg bag.

#### Nitrogen fertilizers

A farmer is advised to apply 40 kg nitrogen per ha to his crop as basal fertilizer at the time of planting. How much calcium ammonium nitrate (CAN) fertilizer should he apply? How many bags of CAN should he buy from a fertilizer dealer?

**Solution**

- According to the fertilizer recommendation the farmer would apply 40 kg nitrogen per ha.
- However, the CAN contains only 21% nitrogen, meaning that the amount of CAN required is: \(40 \times 0.21 = 190\) kg CAN.
- Now, one bag of CAN fertilizer weighs 50 kg. Therefore, 190 kg CAN/50 kg/bag = 4 bags.
- Therefore, 4 bags per ha are required.

---

<table>
<thead>
<tr>
<th>Calcium</th>
<th>CAN, gypsum, Calcium oxide, calcium hydroxide, CaCO₃, CaHCO₃, Limestone, Calcium nitrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese</td>
<td>Manganese sulphate (MnSO₄·3H₂O), Manganese chloride (MnCl₂), Manganese carbonate (MnCO₃), Manganese Oxide (MnO₂), Manganous oxide (MnO), Manganese chelate (MnEDTA)</td>
</tr>
<tr>
<td>Zinc</td>
<td>Parent material, atmospheric deposition, Zinc sulphate, Zinc carbonate, zinc oxide, Zinc nitrate, Zinc chloride, Farmyard manure, compost, green manure, Zinc sulphate is the most commonly used source in the world</td>
</tr>
</tbody>
</table>

**Solution**

- According to the fertilizer recommendation the farmer would apply 40 kg nitrogen per ha.
- However, the CAN contains only 21% nitrogen, meaning that the amount of CAN required is: \(40 \times 0.21 = 190\) kg CAN.
- Now, one bag of CAN fertilizer weighs 50 kg. Therefore, 190 kg CAN/50 kg/bag = 4 bags.
- Therefore, 4 bags per ha are required.

Iron, Copper, Boron, Chlorine and Molybdenum are all applied as foliar feed.
4.5 Fertilizer use efficiency

Fertilizer use efficiency is a quantitative measure of the actual uptake of fertilizer nutrient by the plant in relation to the amount of nutrient added to the soil as fertilizer. A common form of expression of fertilizer use efficiency is plant recovery or “coefficient of utilization” of the added fertilizer. This is expressed as

\[
\text{% utilization of added fertilizer} = \frac{\text{Amount of nutrient in the plant derived from the fertilizer}}{\text{Amount of nutrient applied as fertilizer}} \times 100
\]

The concept of fertilizer-use efficiency is much broader. It implies not only the maximum uptake of the applied nutrient by the crop but also the availability of the applied nutrient under variable climatic, edaphic conditions and environmental issues. To study the efficient use of fertilizers is paramount in order to obtain the highest possible yield with a minimum fertilizer application.

4.5.1 Nitrogen use efficiency

The crop responds to the application of nutrients such as nitrogen and phosphorus when the soil is deficient in such nutrients. Due to the several ways of N losses from the soil, there is need to consider the N use efficiency. Nitrogen use efficiency is an important indicator of how fertilizer N is used by a crop. Nitrogen use efficiency has been defined and calculated in several ways (Table 5.3.1): agronomic efficiency (AE), agro-physiological efficiency (APE), apparent recovery efficiency (ARE), physiological efficiency (PE), and utilization efficiency (UE).

Phosphorus fertilizers

A farmer is advised to apply 20 kg phosphorus per ha on his 5-acre field. How many bags of triple super phosphate (TSP) or single super phosphate (SSP) should he buy?

- For the same phosphorus fertilizer recommendation, which type of phosphorus fertilizer (and how much) should he apply to: ground nuts; maize?

Solution

Caution: For phosphorus fertilizers, the % indicated on the bag refers to % available \(\text{P}_2\text{O}_5\); to convert % phosphorus to %P2O5, multiply by 2.3.

- 1 ha is equivalent to 2.47 acres; 5 acres are equivalent to \(\frac{5.0}{2.47} = 2.02\) ha.
- A recommendation of 20 kg phosphorus per ha translates into 20 kg phosphorus per ha \(\times 2.3 = 46\) kg \(\text{P}_2\text{O}_5\)/ha.

Amount of \(\text{P}_2\text{O}_5\) required for 2.02 ha is equal to 46 kg \(\text{P}_2\text{O}_5\)/ha \(\times 2.02\) ha = 93 kg.

- For TSP containing 45% \(\text{P}_2\text{O}_5\), amount of TSP required is \(100/45 \times 93 = 206\) kg TSP, or 206 kg/50 kg/bag = 4 bags.
- SSP is preferred for legumes due its Sulphur content. SSP contains 20% \(\text{P}_2\text{O}_5\), therefore amount of SSP required for 2.02 ha is 100/20 \times 92.5 kg = 462.5 kg, or 462.5 kg/50 kg/bag = 9 bags.
- For maize the farmer can apply TSP or diammonium phosphate (DAP), the latter is preferred to TSP because of its added N content. If he were to apply DAP, the following computations hold:
  - DAP contains 46% \(\text{P}_2\text{O}_5\),
  - Therefore amount of DAP required for 2.02 ha is 100/46 \times 92.5 kg = 201 kg, or 201 kg/50 kg/bag = 4 bags.

Potassium fertilizers

For potassium fertilizers, the percentages indicated on the bag refers to % water-soluble K2O; to convert % potassium to % K\text{2}O, multiply by 1.21.

After soil testing, a farmer is advised to apply 60 kg potassium per ha (60 kg K/ha) to his banana crop. How much muriate of potash (KCl) should he apply?

Solution

- 60 kg K/ha = 60 \times 1.21 K\text{2}O/ha
- Therefore 72.6 K\text{2}O/ha is required \(\times 2.02\) ha = 146.65 kg
- KCl is 60% K\text{2}O.
- KCl required is 100/60 \times 146.65 = 244.4 kgs are required or 244.4/50 \approx 5\) bags/ha

How to assess nutrients supplied by the soil

A portion of the nutrients required for plant growth is met by what can be supplied by the soil. The soil’s capacity to supply these nutrients depends on several factors which include:

- **Soil organic matter levels**: the higher the soil organic matter level the higher the nutrient supply potential of the soil.
- **Soil texture**: clay soils have a greater capacity to retain nutrients and soil organic matter than sandy soils. Therefore, clay soils tend to have a greater nutrient...
Table 4.5.1 Definitions and methods of calculating Nitrogen Use Efficiency

<table>
<thead>
<tr>
<th>Nutrient Efficiency</th>
<th>Definitions and formulas for calculation</th>
</tr>
</thead>
</table>
| Agronomic efficiency (AE)     | The agronomic efficiency is defined as the economic production obtained per unit of nutrient applied. It can be calculated by: $AE (kg/kg) = \frac{G_f - G_u}{N_a}$  
Where: $G_f$ is the grain yield of the fertilized plot (kg)  
$G_u$ is the grain yield of the unfertilized plot (kg)  
$N_a$ is the quantity of N applied (kg) |
| Physiological efficiency (PE) | Physiological efficiency is defined as the biological yield obtained per unit of nutrient uptake. It can be calculated by: $PE (kg/kg) = \frac{BY_f - BY_u}{N_f - N_u}$  
Where:  
$BY_f$ is the biological yield (grain plus straw) of the fertilized plot (kg)  
$BY_u$ is the biological yield of the unfertilized plot (kg)  
$N_f$ is the N uptake (grain plus straw) of the fertilized plot (kg)  
$N_u$ is the N uptake (grain plus straw) of the unfertilized plot (kg) |
| Agro-physiological efficiency (APE) | Agro-physiological efficiency is defined as the economic production (grain yield in case of annual crops) obtained per unit of nutrient uptake. It can be calculated by: $APE (kg/kg) = \frac{G_f - G_u}{N_{uf} - N_{uu}}$  
Where:  
$G_f$ is the grain yield of fertilized plot (kg)  
$G_u$ is the grain yield of the unfertilized plot (kg)  
$N_{uf}$ is the N uptake (grain plus straw) of the fertilized plot (kg)  
$N_{uu}$ is the N uptake (grain plus straw) of the unfertilized plot (kg) |
| Apparent recovery efficiency (ARE) | Apparent recovery efficiency is defined as the quantity of nutrient uptake per unit of nutrient applied. It can be calculated by:  
$ARE (%) = \frac{N_f - N_u}{N_a} \times 100$  
Where:  
$N_f$ is the N uptake (grain plus straw) of the fertilized plot (kg)  
$N_u$ is the N uptake (grain plus straw) of the unfertilized plot (kg)  
$N_a$ is the quantity of N applied (kg) |
| Utilization efficiency (UE) | Nutrient utilization efficiency is the product of physiological and apparent recovery efficiency. It can be calculated by:  
$UE (kg/kg) = PE \times ARE$ |
supply potential than sandy soils.

- **The capacity of the soil to bind nutrients:** This applies mainly to phosphorus. Soils that bind phosphorus cover wide areas in SSA. These soils have low supply potential of phosphorus although their total soil P may be high.

Soil organic matter contains most nutrients required for plant growth. However, many of these nutrients exist in very small quantities, and will need to be complemented by fertilizers. In cropping systems where farmers have significant amount of organic matter, such as animal manure, the organic matter can be a dominant source of nutrients, particularly nitrogen and sulphur, and be complemented by some fertilizers.

Knowledge of fertilizers is also important to determine the Right Source. Fertilizers are normally sold with a grade, or guaranteed minimum nutrient contents. The primary nutrients (N, P and K) are expressed as percent N-P$_2$O$_5$-K$_2$O. They are always given in this sequence - the first number represents N content; the second available P as P$_2$O$_5$, and the third, soluble K as K$_2$O equivalent. For example, for a compound fertilizer labeled 7-14-7, this means nutrient content of the fertilizer is 7% N, 14% P$_2$O$_5$, and 7% K$_2$O, which translates to 7%N, 6%P and 6%K respectively. For fertilizers containing other nutrients, additional numbers can be added with the chemical symbol of the nutrient; for example, a 21-0-0-24S fertilizer contains 21% N and 24% S only. On fertilizer label, P is expressed in its oxide form P$_2$O$_5$, and K in the oxide form K$_2$O.

To convert from the oxide form to the elemental form, use the following conversion factors:

**For phosphorus,**

\[
%P = \%P_2O_5 \times 0.44 \\
\text{or} \quad P \times 2.29 = P_2O_5
\]

**For potassium,**

\[
%K = \%K_2O \times 0.83 \\
\text{or} \quad K \times 1.20 = K_2O
\]

This means that there is only 44% P in the weight of P$_2$O$_5$, the rest of the weight is oxygen, whereas there is 83% K in the weight of K$_2$O. For example, if a farmer applies two 50 kg bags/ha (100 kg total) of a 17-17-17 grade fertilizer, the total amount of nutrients applied will be 17 kg N, 17 kg P$_2$O$_5$ and 17 kg K$_2$O.

In terms of N, P and K applied, this is equivalent to:

- 17 kg N,
- \(17 \times 0.44 = 7.5\) kg P
- \(17 \times 0.83 = 14\) kg K

**Nutrient contribution of organic sources**

Organic resources are crucial source of various forms of nutrients. Plants of the leguminous family, fix a significant amount of nitrogen into the soil.

---

**Table 4.5.2 Nitrogen fixing capacity of various leguminous species**

<table>
<thead>
<tr>
<th>Species</th>
<th>Potential BNF rate (N/ha/yr)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acacia mangium</td>
<td>50-100</td>
<td>Atangana <em>et al</em> 2014; Chaturvedi <em>et al</em> 2009</td>
</tr>
<tr>
<td>Casuarina Equisetifolia</td>
<td>362</td>
<td>Atangana <em>et al</em> 2014; Nygreg <em>et al</em> 2012</td>
</tr>
<tr>
<td>Faidherbia albida</td>
<td>20</td>
<td>Nair 1993</td>
</tr>
<tr>
<td>Gliricidia sepium</td>
<td>50-100</td>
<td>Chaturvedi <em>et al</em> 2009</td>
</tr>
<tr>
<td>Leucaena leucocephala</td>
<td>100-500</td>
<td>Atangana <em>et al</em> 2014; Chaturvedi <em>et al</em> 2009</td>
</tr>
<tr>
<td>Sesbania rostrata</td>
<td>100-500</td>
<td>Chaturvedi <em>et al</em> 2009</td>
</tr>
<tr>
<td>Tephrosia vogelii</td>
<td>100</td>
<td>Werner, 2005; FAO 2010</td>
</tr>
<tr>
<td>Cajanus cajan</td>
<td>91</td>
<td>Werner, 2005; FAO 2010</td>
</tr>
<tr>
<td>Crotalaria grahamiana</td>
<td>142</td>
<td>Werner, 2005</td>
</tr>
<tr>
<td>Crotalaria juncea</td>
<td>129</td>
<td>Becker, 1995; FAO 2010</td>
</tr>
<tr>
<td>Mucuna pruriens</td>
<td>130</td>
<td>Werner, 2005; FAO 2010</td>
</tr>
<tr>
<td>Stylosanthes hamata</td>
<td>67-112</td>
<td>Nguluu, 1994</td>
</tr>
</tbody>
</table>
This contribution substitutes the amount of mineral fertilizers that the farmers need to apply to meet the recommendation for various crops. The leguminous plants can either be agro-forestry trees or green manure and could be grown in various spatial or temporal arrangements in the cropping system. They could be grown as intercrops, rotations, fallows, alley cropping etc. in addition to supplying nutrients the organic resources are crucial for soil structure and soil physical characteristics. These organic resources contribute to the soils through incorporation, leaf fall, exudation, and nitrogen fixation (Table 5.3.3).

Table 5.3.3: Average NPK contents of plant based organic resources

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Plant part</th>
<th>%N</th>
<th>%P</th>
<th>%K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acacia angustissima</td>
<td>Leaves</td>
<td>3.2</td>
<td>0.17</td>
<td>-</td>
</tr>
<tr>
<td>Calliandra calothyrsus</td>
<td>Leaves</td>
<td>3.3</td>
<td>0.17</td>
<td>0.8</td>
</tr>
<tr>
<td>Leucaena leucocephala</td>
<td>Leaves</td>
<td>3.9</td>
<td>0.19</td>
<td>2.1</td>
</tr>
<tr>
<td>Tephrosia vogelii</td>
<td>Leaves</td>
<td>2.9</td>
<td>0.18</td>
<td>1.1</td>
</tr>
<tr>
<td>Crotalaria Grahamiana</td>
<td>Leaves</td>
<td>3.0</td>
<td>0.13</td>
<td>0.8</td>
</tr>
<tr>
<td>Crotalaria Juncea</td>
<td>Leaves</td>
<td>3.8</td>
<td>0.16</td>
<td>1.3</td>
</tr>
<tr>
<td>Mucuna pruriens</td>
<td>Leaves</td>
<td>4.4</td>
<td>0.30</td>
<td>1.6</td>
</tr>
<tr>
<td>Sesbania sesan</td>
<td>Leaves</td>
<td>1.0</td>
<td>0.13</td>
<td>0.7</td>
</tr>
<tr>
<td>Tithonia diversfolia</td>
<td>Leaves</td>
<td>3.2</td>
<td>0.50</td>
<td>3.5</td>
</tr>
<tr>
<td>Desmodium intortum</td>
<td>Leaves</td>
<td>2.2</td>
<td>0.15</td>
<td>1.2</td>
</tr>
<tr>
<td>Flemingia macrophylla</td>
<td>Leaves</td>
<td>2.7</td>
<td>0.16</td>
<td>0.7</td>
</tr>
<tr>
<td>Pigeon pea</td>
<td>Leaves</td>
<td>3.3</td>
<td>0.19</td>
<td>1.3</td>
</tr>
<tr>
<td>Groundnut</td>
<td>Leaves</td>
<td>3.0</td>
<td>0.17</td>
<td>2.4</td>
</tr>
<tr>
<td>Soybean</td>
<td>Leaves</td>
<td>3.6</td>
<td>0.15</td>
<td>2.4</td>
</tr>
<tr>
<td>Beans</td>
<td>Leaves</td>
<td>2.9</td>
<td>0.30</td>
<td>2.8</td>
</tr>
<tr>
<td>Cowpea</td>
<td>Leaves</td>
<td>2.9</td>
<td>0.11</td>
<td>2.1</td>
</tr>
<tr>
<td>Rice</td>
<td>Straw</td>
<td>1.0</td>
<td>0.06</td>
<td>1.4</td>
</tr>
<tr>
<td>Maize</td>
<td>Straw</td>
<td>0.9</td>
<td>0.07</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 5.3.4. Nutrient content of various types of manure

<table>
<thead>
<tr>
<th>Manure</th>
<th>Moisture %</th>
<th>% N</th>
<th>% P$_2$O$_5$</th>
<th>%K$_2$O</th>
<th>%CaO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmyard manure</td>
<td>38 – 54</td>
<td>0.5 – 2.0</td>
<td>0.4 – 1.5</td>
<td>1.2 – 8.4</td>
<td>0.3 – 2.7</td>
</tr>
<tr>
<td>Cattle dung</td>
<td>34 – 40</td>
<td>1.7 – 2.0</td>
<td>0.5 – 3.7</td>
<td>1.3 – 2.5</td>
<td>0.9 – 1.1</td>
</tr>
<tr>
<td>Sheep and goats droppings</td>
<td>40 – 52</td>
<td>1.5 – 1.8</td>
<td>0.9 – 1.0</td>
<td>1.4 – 1.7</td>
<td>0.9 – 1.0</td>
</tr>
<tr>
<td>Pig manure</td>
<td>35-50</td>
<td>1.5 – 2.4</td>
<td>0.9 – 1.0</td>
<td>1.4 – 3.8</td>
<td>1.3 – 1.5</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>10 – 13</td>
<td>2.3 – 2.5</td>
<td>2.3 – 3.9</td>
<td>1.0 – 3.7</td>
<td>0.6 – 4.0</td>
</tr>
<tr>
<td>Compost manure</td>
<td>49 – 52</td>
<td>0.5 – 1.66</td>
<td>0.3 – 0.5</td>
<td>5.0 – 7.4</td>
<td>4.6 – 5.4</td>
</tr>
</tbody>
</table>
5.0 FIELD RESEARCH METHODOLOGY AND APPROACHES

5.1 Planning and conducting Field experimentation
Soil fertility and plant nutrition research activities are mainly conducted under controlled environments (greenhouse or growth chamber) and under uncontrolled field conditions. Controlled, as well as uncontrolled field, experimentations are essential for developing a sound, efficient, and economical viable technology for improving crop yields.

Basic Considerations for Conducting Field Experimentation
For conducting field experimentations, a researcher should follow these steps for achieving successful results. These considerations are: i) hypothesis and objectives should be well defined, ii) selection of appropriate experimentation site, iii) adequate land preparation, iv) appropriate plot size, shape, and orientation, v) selection of appropriate experimental design, vi) selection of adequate nutrient levels or treatments, vii) use of adequate seed rate, row, and plant spacing, viii) conducting required cultural practices such as control of insects, diseases, weeds, topdressing N, and irrigation, ix) collection of yield and yield data components, x) harvesting at physiological maturity, xi) replication of field experiment at least for two years, xii) use of adequate statistical methods for data analysis, xiii) appropriate divulgation of experimental results in scientific journal, book chapters, or technical bulletins.

5.2 Hypothesis and Objectives
A scientific experiment is conducted to answer some questions or to solve problems. In agriculture, field experiments are designed on the basis of priority of problems to improve crop production. In the field of soil fertility, it may be necessary to determine optimum levels of nutrients for a crop in a particular soil. A hypothesis is a statement about the parameter or parameters in one or more populations. A hypothesis typically arises in the form of speculation concerning observed phenomena of nature or man. An example of a hypothesis is improved cultivars need more nutrients, Oxisols of tropical soils are deficient in phosphorus and micronutrients are not yield limiting factors in newly cleared forestlands. The statistical hypothesis under test is often referred to as the null hypothesis. Once a hypothesis is formed, the next step is to design a procedure for its verification. This is the experimental procedure. When experimental procedures are outlined, the objectives should be clearly defined. What answers does the researcher want from the study under investigation? For example, what would be the optimum levels of nitrogen (N) and phosphorus (P), or what would be the best method of application, etc. A review of pertinent literature is a valuable aid in evaluating a hypothesis and achieving the objectives of an experiment. A review of the literature can determine what type of experimental work was done in the past to the related problem, how it was done, and what results were obtained. The review of literature will help the researcher from the planning stage of the experiment all the way to the interpretation of results.

5.3 Site selection
Sites should be a representative of a large production area for purposes of appropriate extrapolation. Sites should be selected to match the objectives of the study. The trial sites may be at research centres (on-station) and/or in farmer’s fields (on-farm).

Criteria for on-farm site selection
a) The farmer should be sociable
b) Good physical accessibility of the site
c) Adequacy of size and shape of land for experimentation
d) Absence of trees and hedges within the experimental plot
e) Absence of termite moulds within the experimental plot
f) Uniformity of previous land use within the experimental plot
g) Farmer’s willingness to cooperate
h) Site is secure: low risk of animal damage or theft
i) Availability of the site for the entire period of experimentation
j) Farmer management should be representative of other local farms.
5.4 Geo-referencing

Geo-referencing is the process of assigning real-world coordinates to each pixel of the raster. Many times these coordinates are obtained by doing field surveys - collecting coordinates with a GPS device for few easily identifiable features in the ground, satellite images or maps.

To geo-reference means to associate something with locations in physical space. The term is commonly used in the geographic information systems field to describe the process of associating a physical map or raster image of a map with spatial locations. Geo-referencing may be applied to any kind of object or structure that can be related to a geographical location, such as points of interest, roads, places, bridges, or buildings.

At the plot level, basic site characteristics are described and recorded. Initially, geo-reference the centre of the plot by letting the GPS averages the position for at least 5 minutes. Store this as a waypoint in the GPS, and record the easting (longitude), northing (latitude), elevation and position error on the field-recording sheet. Decimal degrees and decimals

Geographic locations are most commonly represented using a coordinate reference system, which in turn can be related to a geodetic reference system such as WGS-84.

Examples include establishing the correct position of an aerial photograph within a map or finding the geographical coordinates of a place name or street address (Geo-coding).

Justification

- Geo-referencing is crucial to making aerial and satellite imagery, usually raster images, useful for mapping as it explains how other data, such as the above GPS points, relate to the imagery.
- Very essential information may be contained in data or images that were produced at a different point of time. It may be desired either to combine or compare this data with that currently available. The latter can be used to analyze the changes in the features under study over a period of time.
- Different maps may use different projection systems. Geo-referencing tools contain methods to combine and overlay these maps with minimum distortion.
- Using geo-referencing methods, data obtained from surveying tools like total stations may be given a point of reference from topographic maps already available.
- It may be required to establish the relationship between social survey results which have been coded with postal codes or street addresses and other geographic areas such as census zones or other areas used in public administration or service planning.

Methods

There are various GIS tools available that can transform image data to some geographic control framework, like the commercial Arc Map, PCI Geomatica, TNTmips (MicroImages, Inc) or ERDAS Imagine. One can geo-reference a set of points, lines, polygons, images, or 3D structures. For instance, a GPS device will record latitude and longitude coordinates for a given point of interest, effectively geo-referencing this point. A geo-reference must be a unique identifier. In other words, there must be only one location for which a geo-reference acts as the reference.

Images may be encoded using special GIS file formats or be accompanied by a world file.

To geo-reference an image, one first needs to establish control points, input the known geographic coordinates of these control points, choose the coordinate system and other projection parameters and then minimize residuals. Residuals are the difference between the actual coordinates of the control points and the coordinates predicted by the geographic model created using the control points. They provide a method of determining the level of accuracy of the geo-referencing process.

In situations where data has been collected and assigned to postal or area codes, it is usually necessary to convert these to geographic coordinates by use of a definitive directory or gazetteer file. Such gazetteers are often produced by census agencies, national mapping organizations or postal service providers. At their simplest, these may simply comprise a list of area codes or place names and another list of corresponding codes, names or coordinate locations. The range and purpose of the codes available is country-specific. An example is the UK’s National Statistics Postcode Directory which shows each postcode’s membership of census,
administrative, electoral and other geographical areas. In this case, the directory also provides dates of creation and deletion, address counts and an Ordnance Survey grid reference for each postcode, allowing it to be mapped directly. Such gazetteer files support many web-based mapping systems which will place a symbol on a map or undertaken analysis such as route-finding, on the basis of postal codes, addresses or place names input by the user (Hackeloeer et al 2014).

5.5 Field experimentation

The experiment is an important tool of research. Some important characteristics of a well planned experiment are:

1. Simplicity: The selection of treatments and the experimental arrangement should be as simple as possible, consistent with the objectives of the experiment.

2. Degree of precision: The probability should be high that the experiment will be able to measure differences with the degree of precision the experimenter desires. This implies an appropriate design and sufficient replication.

3. Absence of systematic error: The experiment must be planned to ensure that experimental units receiving one treatment in no systematic way differ from those receiving another treatment so that an unbiased estimate of each treatment effect can be obtained.

4. Range of validity of conclusion: Conclusions should have as wide a range of validity as possible. An experiment replicated in time and space would increase the range of validity of the conclusions that could be drawn from it. A factorial set of treatments is another way for increasing the range of validity of an experiment. In a factorial experiment the effects of one factor are evaluated under varying levels of a second factor.

5. Calculation of degree of uncertainty: In any experiment there is always some degree of uncertainty as to the validity of the conclusions. The experiment should be designed so that it is possible to calculate the probability of obtaining the observed results by chance alone.

Steps in experimentation

The selection of a procedure for research depends, to a large extent, on the subject matter in which the research is being conducted, and on the objectives of the research. The research might be descriptive and involve a sampling survey, or it might involve a controlled experiment or series of experiments. When an experiment is involved there are a number of considerations that should be carefully thought through if it is to be a success. The following are some of the more important steps to be taken:

1. Definition of the problem: The first step in problem solving is to state the problem clearly and concisely. If the problem cannot be defined there is little chance of it ever being solved. Once the problem is understood, formulate questions which when answered will lead to solutions.

2. Statement of objectives: This may be in form of questions to be answered, the hypothesis to be tested, or the effects to be estimated. Objectives should be written out in precise terms. This allows the experimenter to plan the experimental procedures more effectively. When there is more than one objective, they should be listed in order of importance, as this might have a bearing on the experimental design. In stating objectives do not be vague or too ambitious.

3. Selection of treatment: The success of the experiment rests on the careful selection of treatments, whose evaluation will answer the questions posed.

4. Selection of experimental material: In selecting experimental material, the objectives of the experiment and the population about which inferences are to be made must be considered. The material used should be representative of the population on which the treatments will be tested.

5. Selection of experimental design: Here again, a consideration of objectives is important, but a general rule would be to choose the simplest design that is likely to provide the precision you require.

6. Selection of the unit for observation and the number of replications: For example, in a field experiment with plants, this means deciding on the size and shape of field plots. In experiments with animals, this means deciding on the number of animals to consider as an experimental unit. Experience from other similar experiments is invaluable in making these decisions. Both plot size and the number of replications should be chosen to produce the required precision of treatment estimate.

7. Control of the effects of the adjacent units on each other: This is usually accomplished through the use
8. Consideration of data to be collected: The data collected should properly evaluate treatment effects in line with the objectives of the experiment. In addition, consideration should be given to collection of data that will explain why the treatments perform as they do.

9. Outlining statistical analysis and summarization of results: Write out the sources of variation and associated degrees of freedom in the analysis of variance. Consider how the results might be used, and prepare possible summary tables or graphs that will show the effects expected. The expected results should be compared to the experiment objectives to see if the experiment will give the expected answers.

10. Conducting the experiment: In conducting the experiment, use procedures that are free from personal biases. Make use of the experimental design in collecting data so that differences among individuals or differences associated with order of collection can be removed from experimental error. If it is necessary to copy data, check the copied figures against the originals immediately.

11. Analyzing data and interpreting results: All data should be analyzed as planned and the results interpreted in the light of the experimental conditions, hypothesis tested, and the relation of the results to facts previously established. Do not jump to a conclusion, even though it is statistically significant if the conclusion appears out of line with previously established facts. In this case investigate the matter further.

12. Preparation of a complete, readable, and correct report of the research: There is no such thing as negative results. If the null hypothesis is not rejected, it is positive evidence that there may be no real differences among the treatments tested. Check with other researchers and provide for review of the conclusions reached.

**Basic definitions and concepts**

**On-station research**: On station research can be defined as research carried out in a researcher-designed and managed environment. Often this is done in a research station, university farm, or other types of environment where researchers have full control.

**On-farm research**: On-farm research (OFR) is research carried out on farmer’s fields. It can be researcher designed farmer managed or researcher designed and managed by researchers or both the farmer and the researcher. Four key elements in OFR include: the farmer, the farmer’s land, the farmer’s involvement, and the farmer’s environment.

**Experiment**: A test under controlled conditions, often called a trial, to test hypotheses or obtain information on the efficacy of various treatments/interventions.

**Experimental unit**: The lowest unit, to which a treatment is applied, e.g. plot or sub-plot. The information or-data for comparison are derived from such single units and combined for purposes of analysis and comparisons. Examples include a single animal or group of animals receiving the same feed from the same source, a small plot having the same type of trees or agricultural crops.

**Experimental treatment**: A controlled or combination of controlled variables imposed/applied to experimental units by the researcher; e.g. 60N-0P-0K applied to plot 103. The treatment is the material being used on the subject (unit) and whose effect is to be monitored. Factor and treatment are words often used interchangeably in research. A factor has levels, e.g. an N factor has at least two levels of N tested at zero level and any other value above zero.

**Experimental factor**: A controlled category of levels or treatments under investigation, e.g. N, P, or farmyard manure. Factors have 2 or more levels set by the experimenter, e.g. 0, 7.5, 15, 22.5 kg/ha P. A tillage factor may have levels of no-till, tie-ridging, or tillage without ridges. A trial may be set to test a single factor or interaction between factors. A good example is in a fertilizer rates trial superimposed on a tillage experiment to test the interaction between fertilizers and tillage levels.

**Sample**: Part of a population used to describe the entire population, e.g. treatment applied to an experimental unit, but also plot area harvested for yield determination or soil analysis. The sample should be a representative of the population. To obtain a representative sample, the principle of randomness is used. A random sample is one in which any individual measurement is as likely to be included as any other.
Block: It is the grouping of a set of the experimental units into homogenous set. A block is a relatively large area or several identical units receiving all or most of the treatments (A full set of treatments and equivalent to one replication). Blocking is done to minimize variability across the treatments under comparison. Variability can be introduced by differences in current management, management history, topography, soil type and climatic conditions. In a field experiment plots physically closer to each other or having similar soil properties would be expected to be characteristically more homogenous than plots far apart.

Experimental error is a measure of the sum of variation between plots or units receiving same treatments. Care should be taken to reduce experimental error to facilitate robust comparison of treatments effects.

**Experimental design**: The plan for grouping of experimental units and assigning treatments to them. Examples commonly used designs include RCBD, CRD, Split-plot, etc.

**Randomization**: The process by which treatments are allocated by chance to experiment units/plots; each treatment has an equal chance to be applied to an experimental unit. The analysis of variance assumes that treatments have been applied randomly. Randomization can also be applied in research setting but more frequently sites should be selected after careful consideration of the research objectives.

**Replication**: This means repetition of a treatment within an experiment or trial. Complete replications are the number of times a treatment appears in an experiment.

**Population**: It is defined as a complete set of items that share at least one property in common that is the subject of statistical analysis.

**Trial site**: A research area encompassing the exact land area, delineated by latitude and longitude coordinates, occupied by a trial. A site may have more than one trial addressing more than one research query. A site-season refers to a trial conducted at that site during a given season.

5.5.1 Experimental design & Layout
As described earlier, On-station research can be defined as research carried out in a researcher-designed and managed environment. Often this is done in a research station, university farm, or other types of environment where researchers have full control. On the other hand On-farm research is research carried out on farmer’s fields. It can be researcher designed farmer managed or researcher designed and managed by researchers or both the farmer and the researcher. Four key elements in OFR include: the farmer, the farmer’s land, the farmer’s involvement, and the farmer’s environment.

Why conduct On-farm research (OFR) On-farm research is done for: testing and validation of farming technologies under local farmer’s conditions; development and adaptation of farming technologies for local farmers’ conditions, and demonstration and extension of farming technologies in local farming communities. There are basically two types of OFR:

(a) **Experimental OFR**: This is the more commonly known and practiced of the two types of OFR. It is performed for bio-physical, technical, and economic assessment of alternative systems or treatments within the framework of standard experimental designs. Bio-physical assessment aims at determining the system’s biological and physical yield and productivity, while economic assessment inquires into the availability of labour, cash, and other resources for meeting the projected needs of the alternative system, and looks into the level and stability of profit.

On-farm research trials emanate directly from on-station research. Their structure and design are very similar to those used on-station. However, on-farm experimentation is kept as simple as possible to ensure effective farmer understanding of issues and meaningful involvement and contribution. Depending on the nature of farmer/researcher involvement in the trials, OFR may be further classified into three different types, namely:

(i) **Researcher-managed trials**: The researcher is responsible for directing and implementing the treatments in accordance with the chosen design and methodology of the trial. A single farmer’s field could be used for such a trial, though this may be repeated on another farmer’s plot (if required). The
farmer and researcher may have a landlord/tenant relationship (with the lowest degree of farmer involvement). Here a researcher obtains a plot of land from a farmer’s holding to carry out an OFR activity in which the farmer has no part to play. The farmer may also have no direct interest in what is going on, and may consider his or her involvement only as having given land (on lease, on loan, or as gift) for research activity.

Alternatively, the farmer may have a passive on-looker involvement. In this case also, the farmer makes land available, but has no direct role in the management or operation of the trial. The major difference between this and the landlord/tenant relationship is that in this case, the research is carried out on the same piece of land that the farmer is cultivating. The researcher may, from time to time, invite the farmer to observe particular operations or see some emerging responses. Such a situation usually arises in researcher-managed OFR trials superimposed on existing farmer plots.

(ii) Researcher/farmer-managed trials: These are trials in which management and operation are the joint responsibility of farmer and researcher. The farmer administers the experimental inputs as prescribed by the researcher and controls all other factors related to crop or livestock management. Researcher-managed trials are very similar in structure to on-station trials. Such trials need to be made simpler than the researcher-managed trials, since an increased level of farmer’s involvement is required. Simplicity ensures a better understanding of the trial by the farmer.

The farmer’s role may be termed active involvement (researcher-controlled), as the farmer is directly involved in carrying out some or all of the management operations in the trial. However, the farmers’ contribution is very clearly defined and controlled by the researcher. He is therefore unable to use his initiative, and does what the researcher has programmed for him to do in terms of treatment applications and management requirements.

(iii) Farmer-managed trials: In farmer-managed OFR, the farmer is responsible for carrying out almost all management operations for the trial. The farmer manages all experimental inputs in the manner in which he or she sees fit and the researcher observes the manner in which the technology is applied. An even higher level of simplicity is thus required, and the number of unit plots within a single farmer’s field is kept at a minimum to reduce complications for the farmer.

The farmer’s role is active involvement (farmer-controlled). The farmer is made to see the trial as his or her own, and is free to make modifications in the management of the system being tested and to identify problem aspects of the system. The researcher takes on what may be described as an “active on-looker” role in this process, making regular observation of the farmer’s performances, responses, attitudes, impressions, and opinions, as well as the biological and technical performance of the system being tested.

Criteria for Adopting Researcher-managed or Farmer-managed Trials: The main consideration for carrying out one or the other type of experimental OFR is the level of knowledge and confidence about the technology in question. Technologies for which sufficient information is not available are generally tested under researcher-managed trials with a high degree of control by the researcher. But technologies for which enough accurate information is available are carried out under researcher/farmer-managed trials or under farmer-managed trials. A generalization about the three types of trials is that researcher-managed trials are technology generation trials while the other two aim at technology validation or demonstration.

(b) Developmental OFR: This type of OFR activity has received less attention than the experimental type. It involves (1) the introduction of particular systems within the farmer environment and (2) the assessment of the workability of the system and its acceptability by farmers. Developmental OFR operates within a framework of research-extension collaboration. Its main purpose is the extrapolation of the tested results to the target area. An attempt is made to fine-tune the technology and to determine the required support structures prior to wide-scale extension of the technology. Through the developmental OFR process, farmers of the targeted
area are gradually exposed to a new technology, and their management of the system is monitored in order to identify problem areas and researchable issues.

Developmental OFR makes use of extension techniques and methodologies for the introduction of the concept or system and development of farmer’s awareness. For this reason, developmental OFR requires the joint involvement of researchers, farmers and extension agents.

Types of Field Experiments: The several types of experimental trials include:
- Variety trials;
- Provenance trails;
- Field germplasm or screening trials;
- Fertilizer trials;
- Cultural/agronomic trials;
- Chemical (other than fertilizer) trials.

It is quite common to have more than one type of trial in the same experiment. For instance we can compare different hedgerow species under weeding and no-weeding, that is, a situation involving both variety and cultural trials.

Experimental design: This is the allocation of treatments (inputs) to the experimental units (plots). It is the plan for grouping experimental units and assigning treatments to them.

Experimental design is a way to arrange treatments in a field so that error and bias are reduced and the data may be accurately analyzed using statistics. Standard experimental formats or designs are usually used in on-farm research.

The criterion used to select which design fits which experiment depends on the number of treatments under investigation. The choice of design is influenced by several considerations: the objectives, the amount of resources, and the time available.

Replication, randomization, and use of a control are essential in designing an experiment because they help to separate out treatment effects from natural levels of background variation.

5.5.2 Types of experimental designs
- Completely randomized design (CRD)

The completely randomized design is the simplest experimental design. In a completely randomized design, treatment levels or combinations are assigned to experimental units at random. In CRD, each experimental unit has an equal chance of receiving a certain treatment. Here, treatments are replicated but not blocked, which means that the treatments are assigned to plots in a completely random manner. This is typically done by listing the treatment levels or treatment combinations and assigning a random number to each. By sorting on the random number, a random order for application of the treatments to experimental units is produced.

This design is appropriate if the entire test area is homogeneous (uniform in every way that can influence the results). Unfortunately, it is rare that you can ever be confident of a test sites uniformity, so a completely randomized design is rarely used in field tests. The completely randomized design is used more commonly in greenhouse tests, though blocking is often useful even in the more controlled environment of a greenhouse (Davis et al., 1999).

- The randomized complete block design (RCBD)

The randomized complete block design (RCBD) is the most commonly used design in agricultural field research. In this design, treatments are both replicated and blocked, which means that plots are arranged into blocks and then treatments are assigned to plots within a block in a random manner. Randomized Complete Block Design (RCBD) is characterized by the presence of equally sized blocks, each containing all of the treatments. This design is most effective if you can identify the patterns of non-uniformity in a field such as changing soil types, drainage patterns, fertility gradients, direction of insect migration into a field, etc. If you cannot identify the potential sources of variation, you should still use this design for field research but make your blocks as square as possible. This usually will keep plots within a block as uniform as possible even if you cannot predict the variation among plots.

- Factorial design

A factorial arrangement of treatments is not an experimental design, though it is often common to hear it being referred to as a factorial design or
a factorial experiment. A factorial arrangement of treatments means that the experiment is testing two or more factors at the same time, and that the experiment includes all combinations of all factors. The term factor is used to describe a group of treatments that have something in common. Fungicides, sources of nitrogen, or rice varieties could be considered factors in an experiment. Factors may be defined broadly or narrowly in different experiments. All herbicides may be grouped as a factor in one experiment, but pre-plant and post-plant herbicides may be treated as separate factors in another experiment. A single-factor experiment tests one factor at a time; a two-factor experiment tests two factors at once. It is sometimes useful to test two or more factors at once. For example, a two-factor experiment would allow you to compare the yields of five rice varieties at three planting dates. This accomplishes three things at once: 1. It allows one to compare the rice varieties to each other. 2. It allows you to evaluate the effect of planting date. 3. It allows you to determine if varying the planting date changes the relative performance of the varieties (e.g. one variety may only perform well if planted early).

**Split plot design**
A split-plot experimental design is a special design that is sometimes used with factorial arrangements of treatments. This design usually is used when an experiment has at least two factors and some constraint prevents you from randomizing the treatments into a randomized complete block design. Such a constraint may be based on equipment limitations, on biological considerations or when certain treatments require a larger plot size than others. For example, the equipment you have may make it difficult to put out a soil fumigant in randomized complete blocks, but you may be able to put out the fumigant so that all treatments within a block that get the fumigant will be clustered together rather than scattered throughout the block. In split-plot designs, the terms whole plots and subplots refer to the plots into which the factors are randomized. As the names imply, whole plots are subdivided into subplots. To assign treatments in a split-plot design, start by identifying where each block will be. Then randomize the whole plot treatments within each block. The whole plot treatments will be the treatments that you are unable to randomize into a randomized complete block design. The subplot treatments can then be randomized within each whole plot treatment (Davis et al., 1999). Split plots can be applied to two experimental designs: the CRD and RCBD- where one factor is applied to whole plots forming a complete block, and then the second factor is applied to sub-plots within the whole plots within each block. Split plots can be extended to accommodate multiple splits hence split-split-plot experimental design being used.

**Latin square**
The Randomised Complete Block design is useful for eliminating the contribution of one source of variation only. In contrast, the Latin Square Design can handle two sources of variations among experimental units. In Latin Square Design, every treatment occurs only once in each row and each column. The fundamental idea of blocking can be extended to more dimensions. Blocking simultaneously with complete blocks in two directions is accomplished with a Latin Square design. The limitation is that the Latin Square experimental layout will only be possible if the number of Row blocks = number of Column blocks = number of treatment levels.

**Incomplete design**
“Incomplete” in this design simply means all treatments do not occur within the same block. This design should only be used if the experimental situation forces blocks to be too small, but also is recommended if more than 10 treatments are being tested. In the latter case, experience suggests that complete blocks of 10 or more experimental units generally are so large that they will contain experimental units that are not similar. Such blocks should be divided into more homogeneous groups, producing an incomplete block design, because the divided complete block will now be too small to hold all treatments. For Example: When one is working in a greenhouse, and want to compare 9 varieties of flowers. The benches in this greenhouse are only large enough to hold 6 pots, and now the benches differ and so must be blocked on. Here the block size of 6 is too small to hold all 9 treatments, making the blocks “incomplete”. 30
5.5.3 Choice of treatments and units
The objective, or purpose, of the study will determine the treatments to be included in an experiment. Listing the test objectives is crucial because this supports precise definition of the actual objective. A test may have more than one objective, although multiple objectives should be closely related. The selection of treatments is usually logical if one can define the purpose of the study; all treatments necessary to address the tests objective should be included. For example, if the purpose were to determine which of five fungicides works the best, then the treatments would include all five of those fungicides. If the purpose were to determine if any of the five fungicides works better than the current farmer’s choice, then the treatments would include the five fungicides plus the fungicide the farmer is currently using. Accurately stating the purpose of the test before the treatments are applied in the field is critical. It is common to want to test in the same experiment two (or more) things that influence crop production. For example, you may want to test chicken litter as a fertilizer and test five corn hybrids to maximize yield. To do that, the treatment list must include each hybrid without chicken litter and each hybrid with chicken litter; a total of 10 treatments.

How many treatments: There are no general rules prescribing the number of treatments needed. The minimum may be one, when a single new variety is distributed in an adoption study. However, normally there are at least two treatments being compared. Researcher-led on-farm trials usually have more treatments than farmer-led on-farm trials. When selecting treatments for a farmer-led on-farm trial one can advise farmers to keep them simple and few, no more than 3, including the check plot. For robust statistical analysis at least three treatments are required to allow generation of two degrees of freedom. As treatments increase in number, so do the number of plots and the complexity of the on-farm research programme? Treatments should vary enough to detect differences visually and/or by measuring yield. For example, the visible difference in yield between 45 and 55 kg of nitrogen per ha may not be apparent. The difference between 0 and 45 kg of nitrogen per ha, however, may be more obvious. In statistical sense, a difference of 50 or 100 kg of rice per ha between treatments does not necessarily represent any yield advantage. Having control plots where the treatment is not applied gives a basis for comparison. If you are researching a new practice or variety, the control would be a plot that receives the normal practice or variety often referred to as the farmer practice. For example, in variety trials, the control is usually the traditional, established variety whose performance is known. In designing an experiment, it is essential to include a control so that the effects of your treatment can be measured against something not receiving that treatment. In on-farm trials the control is often the farmer’s normal practice.

5.5.4 Replication
Replication and resources
In designing an on-farm trial the researchers need to consider their resources carefully. For precise treatment comparisons there needs to be sufficient replication - but at what level? It is usually preferable to have more farms and fewer repeats of the same treatment per farm, rather than fewer farms and more replication within a farm. This is because research is done for purposes of generalization and generalizing on the basis of a few farms represents bias introduced by differences in management. Consequently, in on-farm experiments, it is frequently the case that there are many farmers but each farmer has only one replicate of each treatment. The problem with having no within-farm replication is that the farmer-treatment interaction is then normally used as the random (or residual) variation. However, the treatment effects may really be different for the different farmers and understanding this interaction, e.g. which treatments are most effective for which types of farmers, may be an objective of the research. We suggest instead that consideration be given to a design where each farmer repeats a single treatment. If there is a reasonable number of a farm in the experiment then this should allow a valid subsequent analysis of the data. The replication should also be sufficient if the data are to be split into two or three subsets for analysis. The choice of which treatment is to be repeated is not critical.

5.5.5 Laying out of the experiment
Crop Experiments: Plot layout
Layout of plots within each farm will primarily be guided by perceived or known variation within the farming area. The farmers’ knowledge about the variation in their fields should be used to determine the location of the plots and any blocking scheme, and to avoid using particular patches of the field where necessary. It is important to ensure that farmers and researchers are using the same criteria to define suitable locations. Researchers normally strive for homogeneity, while farmers may
have particular parts of their field where they would like to try some treatments. For example, they may feel that addition of crop residues is most appropriate on degraded patches. Where large sections of the field are degraded, this can be accommodated within the design by putting all treatments on this type of land. Otherwise the liberty given to farmers will depend on the objectives of the trial. If farmers’ opinions are of paramount importance, then the loss of randomness in the allocation of treatments to plots is of minor concern. The important sampling is at a higher level, namely in the choice of farmers. On the other hand, if a comparison of yields is an important part of the trial, then it is important to allocate treatments “fairly” (i.e. with some element of randomness) to the plots. In such a case, use of the degraded patches could be in addition to a replicate of the treatment on ordinary parts of the field. Many practical considerations need to be taken into account when considering block and plot layout. In an on-station trial, for instance, a split-plot experiment may be carried out because it is convenient to plant one large area at one time, whilst the application of different levels of fertilizer can be on smaller areas. In on-farm trials these considerations may still apply. Another important practical aspect is the interview process. For instance if a farmer is to give an assessment of different varieties, where fertility is a secondary factor, then it may be convenient if the varieties are grouped together.

5.5.6 Plot size and shape

In alley farming, plot shapes are more likely to be square or rectangular than any other shape. A square plot exposes the least number of plants to the edge effect. Avoid circular plots; on sloping grounds, circular plots tend to be ellipses. As regards plot size, plots that are too small yield unreliable results. On the other hand, excessively large plots waste time and resources. Experiments are usually done on portions of the farm, seldom on the entire farm. The mathematical techniques of statistics are used to calculate the odds that what you are measuring on one part of the farm will hold true for the whole farm (Sooby, 2001). In the planning stages, decide what size your plots will be and where they will fit best. On-farm research typically uses plots that are field length and one or two tractor passes wide. This makes it easier to apply treatments along the entire strip without having to start or stop in the middle of the field.

The size of a plot can greatly affect the magnitude of experimental error in a field trial. Too small plots may give unreliable results; unnecessarily large plots waste time and resources.

In general, experimental error decreases as plot size increases, but the reduction is not proportional. Plot size not only affects variability but may also bring about bias in the experimental results. Plots should be wide enough to permit the removal of border rows when necessary.

Whatever size and shape of plots chosen, the area should not be smaller than 5 m², free from all types of competition and border effects, is available for harvesting and determining plot yield. The cultural practices related to the experiment can dictate the size and shape of plots for ease of operations. Fertilizer trials require larger plots than variety yield tests. Irrigation studies may require even larger plots. In insecticide or herbicide trials where the chemicals are to be sprayed, the width of the plot may be governed by the range of coverage of the sprayer used. When soil heterogeneity is patchy a large plot should be used. In experiments where border effects might be appreciable, square plots are desirable because they have minimum perimeter for a given plot size. In varietal yield tests where varietal competition is expected, plots with at least six rows should be used to allow exclusion of one row on each side of the plot, thus leaving four center rows for harvest (Gomez, 1972). To get an accurate measurement of the effect of pest and weed management treatments, the plot must be large enough to account for uneven initial distribution of the pest (pathogen, insect, etc.) and weed. Some diseases and pests are highly mobile and spread very rapidly (such as many insects). In an insect management trial, measuring the effect of a treatment can be very difficult if the plots are too small because the insects that are seen in the plot may have simply spread from the plot next to it. To minimize this problem, increase the plot size and then collect data from the middle section of the plot. For example, have an eight-row plot but only collect data from the middle four rows. The rows from which the data is not collected are often referred to as buffer rows because they buffer the effect of the neighboring plots.

5.5.7 Plot orientation

Irregularly sloped areas should be avoided, but there is no objection to the use of area with a near constant slope provided the plots run up and down the slope. The same principle applies on a fertility gradient. For trials on
terraces, one should ensure that all the treatments (except in incomplete block situations) appear on the same terrace, so that a terrace could be regarded as a block (Rao and Roger, 1990).

5.5.8 Plot marking and labelling
Flags, stakes or fence posts are useful to mark where one treatment ends and the next one begins at planting, when applying treatments, and at harvest. Such markers can easily be knocked over or ripped out with machinery, so be careful and immediately replace any that are moved (Sooby, 2001).

5.5.9 Soil fertility management

Organic matter
Organic matter is critical for maintaining soil structure, and increasing water infiltration as well as water holding capacity. It can also increase cation exchange capacity (CEC), nutrient retention, and microbial diversity and activities. Organic matter can be added through incorporation of cover crops as green manures as well as additions of composts, animal manures, and crop residues. The addition of organic amendments is particularly important in vegetable production where minimal crop residue is returned to the soil and more intensive tillage is required that promotes the rapid depletion of soil organic matter. The impact of various organic amendments on soil physical, chemical and biological properties can be different and thus is important to consider when making soil management decisions.

Manure: Manure containing a lot of bedding is typically applied as a solid while manure with minimal bedding is applied as a liquid. Manure solids and liquids may be separated, or can also be composted prior to application to help stabilize the nutrients. Due to the variability in nutrient content, manure analysis may be beneficial and take the guesswork out of estimating the nutrient content and characteristics of the manure.

Compost: Unlike manure, compost is very stable and not a readily available source of nutrients. The composting process uses heat and microbial activity to quickly decompose simple compounds like sugars and proteins, leaving behind more stable complex compounds such as lignin and humic acids. The stable products of composting are an important source of organic matter. The addition of compost increases available water capacity by improving water retention and pore space on which water and nutrients can bind. Compost is less effective at building soil aggregation than fresh manure, because the readily-degradable organic compounds have already been decomposed. Composts differ in their efficiency to suppress various crop compounds, although they can sometimes be quite effective.

Green manure: Green manure crops are those grown for the purpose of improving the soil fertility with microbial diversity and organic matter content in general as opposed to cover crops which are grown more for the purpose of erosion protection and cycling of nutrients. When incorporated, green manures add a lot of fresh, readily degradable material to the soil, which fuels the soil’s microbial community. The increased production of microbial exudates helps hold the individual soil particles together as aggregates. A soil with better aggregation (aggregate stability) is more resilient in heavy rain storms and is capable of greater water infiltration. In reduced tillage systems, one way to get the added benefits of green manure crops is to only incorporate them in the planting row and use the killed crop between the rows as mulch.

Crop residue: Crop residue is another important source of organic matter. As it decomposes, the organic matter is going back into the soil and improving soil tilth. Crop residue left on the surface will protect against erosion and improve surface aggregation, thereby reducing crusting and surface compaction. However, diseased crop debris can harbour inoculum that can become a problem during the next season if a susceptible crop is planted. Crop rotation with non-host crops belonging to different plant families will reduce pathogen inoculum. Removal and composting of crop debris may be an option in some situations. Incorporation or ploughing down of crop debris to encourage the decomposition process may be an option depending on the tillage system and crop rotation sequence being employed.

Vermi-compost (also wormi-compost): is an important type of compost and organic fertilizer which contains earthworm’s cocoons, excreta, beneficial microorganisms, actinomycetes, plant nutrients, organic matter, enzymes, hormones etc.

Liming: Soils have a natural tendency to become increasingly acidic over time. The increase in soil
acidity may be caused by several management factors, which may be natural and management. Soil acidity can lead to substantial reduction in crop yields and hence serious economic losses to a farmer. On the other hand, increasing acidity can have a negative impact on the environment. Some of the natural causes include the composition of the parent material, native vegetation, leaching, and soil depth. Factors influenced by management include the types of crops grown, ammonium nitrogen fertilization, organic matter decomposition, tillage, and soil erosion. This tendency can be reversed by appropriate use of liming materials to increase crop yields, long-term sustainability and farmer profits.

5.5.10 Agronomic management

Crop management

**Good crop management** is essential to obtaining results needed for development of good nutrient response functions. A very important pre-caution is consideration of seed quality. Verify seed quality by conducting germination tests; discard seed if germination is less than 50% and otherwise adjust seed rates according to the germination percentage.

**Land preparation**: generally the land can be hoe or plough tilled but reduced tillage or no-till options are acceptable if experience indicates this is a preferred or common practice. Land preparation by ploughing can be done to a depth of 15-20 cm using commonly used methods for each site: ox-drawn plough, hand-held hoe, etc. The method used should be recorded. If some farmers are not used to the method adopted it is important to demonstrate it to them to ensure uniformity across different fields. Especially when the hoe is used one should make sure the tilling is done to the required depth (20 cm). Except where land preparation is done after the first rains, land preparation should be done well in advance to ensure all fields are ready in time for planting. Farmers can be busy with their own parcels once the rains set, resulting in late planting of experimental fields. Activities like and preparation, planting and harvesting of 32 diagnostic fields require a lot of work and the technician will need a team of well trained field assistants to be able to finish the work in time. Participation of the farmers and local communities should be encouraged.

**Planting and gapping**

**Planting** needs to be timely and done at the onset of the rainy season in each site, at the same time farmers’ plant their fields. Planting on ridges, in a flat seedbed, basin or other depends on what is customary in the region. However, management of the diagnostic trials should reflect good, optimal management practices. For example, in areas with risk of rainfall shortage or dry spells, measures to increase infiltration and reduce surface runoff would be useful. If ‘tied ridges’ is a practice used by some farmers in the region, it should be applied in the diagnostic trials. The same applies for planting basins or other measures, though these might be adjusted to suite the planting densities prescribed for the diagnostic trials. The way the land is prepared and structures used should be documented. Maize should be planted at a spacing of 75 cm (inter-row) and 25 cm (intra-row) single seeded. Therefore, there will be 20 planting stations per row and seven rows per 5 x 5 m plot. To achieve the desired intra-row spacing, planting ropes should be marked at 25 cm intervals (using ink or knots) and planting holes (or dibbling) made adjacent to the marks. For efficiency, it is appropriate to have two or three planting ropes. Where planting holes are made with hoes, care should be taken to ensure that holes are made on the same side of rope to avoid crooked rows. Planting depth should be 5-7 cm. Two seeds will be planted per station and thinned to one 5-10 days after emergence. Gapping (replacement planting) will be done 5 days after emergence (or about 10 days after planting). Timely gapping will ensure that maturation of the plants within a treatment is not staggered.

**Weed, Pest and disease control**

**Weeds** compete for water, nutrients and light with crops and timely weeding should be undertaken to avoid this. Pesticide application with a systemic insecticide for stem borer control should be routine for maize and sorghum in most cases. Other pesticide applications should be as recommended or based on close monitoring of insect pest and disease pressure.

5.5.11 Data collection

**Observations**

Data collection can be done and recorded on field book sheets with entry into Excel worksheets soon after or digitally with synchronized transfer to computer. The data that should be collected includes:

i. Activities such as date and method of land preparation; planting information including date, variety, seed rate.
ii. General observations on the condition of the crop. Ratings of damage (disease, pests, weeds, striga, animals, hail, etc.) and other observations on a whole trials basis or where observed if localized.

iii. Plot data: Plot level measured observations (use printed labels adhered to all sampling bags to save time in the field and reduce chances of error) will include:

iv. Emergence date and plant population measurement: From the second day after the first coleoptile emerges from the soil, record the total number of stations with emerged plants within the total plot area (5m x 5m). Stop on the date when ½ of all stations have plants emerged. Record this date as the 50% emergence date. For example, with a total of 140 stations in a plot, 50% emergence date will be that date when at least 67 hills have an emerged coleoptile.

5.6 Field limitations
For homogeneity of field experiments:

a) Field should not be affected by regular disposal of wastes and manure or have unusually high nutrient levels, e.g. a former kraal or site of burning

b) Field should not have received a total of >5t/ha manure or organic waste (Excludes crop residue produced in the field) in past 2 years for fertility trials.

c) Field should have been in annual crop production for at least 2 years.

d) If the crop of interest is a cereal and the nutrient of interest is nitrogen then the field should not have been under legume production.

e) Avoid fields with characteristics that may limit response such as

- Barriers to root growth,
- Rocky or very stony, unusually high sand content,
- Uncontrollable pest pressure including difficult to control weeds such as *Striga hermonthica*,
- Limit allocation of plots to slopes of less than 10%. Slopes between 10-25% should be blocked following soil conservation measures e.g. benches, grass trips, agro-forestry contour hedges, stone lines and any other appropriate soil conservation measures.
6.0 PLANTS-SOIL SAMPLING AND ANALYSIS

6.1 Soil Sampling
Soil sampling is necessary and done for various reasons. These include:

- Establish baseline soil nutrient status
- To measure change in soil nutrient status over time
- Determine nutrient application recommendation prior to planting
- Assess the soil pH and the need for liming
- Avoid excessive nutrient application or soluble salts accumulation
- For soil biological characterization (biological activities are important for transformation of soil nutrient into forms that are appropriate for plant uptake; some like mycorrhizae can directly influence uptake)
- For soil physical characteristic evaluation (soil physical characteristics are crucial determinants of the plant rooting pattern)

The area to collect a soil sample depends on soil type, crops to be grown, management history, or all these factors combined.

The method and procedure for obtaining soil samples vary according to the purpose of sampling. This section describes soil sampling procedure for soil fertility evaluation and fertilizer recommendations. The efficiency of soil testing service depends upon the care and skill with which soil samples are collected. Un-representativeness of samples is the largest single source of error in soil fertility assessment. This is because the interpretation is based on only one to ten grams of the soil sub-sampled for chemical determination.

6.1.1 Sampling tools and accessories
In general tools and accessories for soil sampling depends on the purpose and conditions of the soil. The most commonly used tools and accessories are:

a) Soil auger - A tube auger, post hole or screw type auger or even a spade
b) Trowel for mixing soil
c) A clean bucket or a tray or a clean cloth for mixing the soil and for sub-sampling.

d) Permanent markers for labeling
e) Soil sampling information sheet
f) Soil sampling bags/boxes
g) Cooler box
h) Core rings
i) Tape measure/ruler
j) Knife/sample divider
k) Data sheet/note book
l) GPS
m) Stainless augers
n) Scoopers
o) Automatic hydraulic soil samplers
p) Field information (maps, Ariel photo)
q) Clean plastic containers
r) Sampling probe/core

6.1.2 Selection of a sampling unit
A visual survey of the field should precede the actual sampling. Traverse the field and note the variation in slope, colour, texture, management and cropping pattern and demarcate the field into uniform portions, each of which must be sampled separately. The more the number of samples per sampling area the better the representativeness. The unit of sampling is a compromise between the expenditure, labour and time on one hand and precision on the other.

Avoid sampling in small areas where the conditions are different from the rest of the field (former manure piles, fertilizer bands or fence lines). These can be spotted by observing the plant vigour.

6.1.3 Sampling procedure
Prepare a map of the area to be covered showing different sampling unit boundaries. A plan of the number of samples and manner of composite sampling is marked on the map, with different fields designated by letters A, B, C etc. Each area is traversed separately and cores of the plough-layer are made at intervals of 0-20 for top soil and 20-50 cm for sub-soil. However, depending on the sampling objective e.g. when sampling for carbon and microbial studies the soil profile can be sectioned into smaller depths intervals (e.g., 0-10/20 cm, 20-50 cm, 50-80 cm, and 80-110 cm). Before coring remove surface litter and sink a core from the surface to the plough depth.
(0-20 cm) from each sampling point. Depending on the size of the field, soil can be sampled from 5 or more random spots and mixed thoroughly to make up one composite sample. The composite sample is mixed in a clearly labeled bucket and sub-sampled for representative sub-sample presented for laboratory analysis. From the field, samples are packed in clearly labeled sampling bags. Write the details of the sample in the information sheet. A detailed information sheet is presented to the laboratories together with the samples. This is crucial source of information that is used by the laboratory staff to code and achieve the samples. The content of this information sheet include: type of samples the reference researcher, date of sampling, geo-political location (e.g. county, sub county, ward, location, nearest institution)/GPS coordinates, requested analysis, experimental title and code, sampling depth, farm and field codes.

**NB:** It is important to collect samples from all the spots marked for one sampling unit.

As a precautionary measures: Soil samples should never be kept in the store along with chemical materials and detergents that could potentially contaminate the samples. The store for the samples should be kept dry.

**Sampling depth**

Data gathered from more than 20 agricultural research/learning institutions in Kenya within the mandate of the Kenya Soil Health consortium revealed a state of confusion over soil sampling depth. In certain studies the top soils were regarded as those from 0-10 cm depth while other studies used 0-20 cm and 0-30 cm depths for sampling. It is important to note that the appropriate sampling depth is best determined by the intended type of analysis. For microbial analysis, the top soil can be sampled up to 10 cm depth because this is the horizon where most microbial activity take place, but for chemical/soil nutrient status analysis a reference to top soil is 0-20 cm depth because this is regarded as the rooting depth for most of the annual crops. On the other hand for soil physical characteristics the sampling depth may vary depending on the intended use of the soil physical data.

### 6.1.4 Sampling strategy

Since there is no one standard sampling procedure recommended for all countries and that is suitable for all soils, several soil sampling strategies are used in different countries. In the Netherlands, a minimum of 40 cores are made on arable land of an area of 2 ha to 30 cm depth for fertilizer recommendation. In Kenya 9 core samples were found to be adequate for fields of about 0.5 ha to detect differences in nutrient status of soils in many parts of Kenya (Okalebo et al., 1992). The number of cores to be taken depends on the acceptable coefficient of variation (cv) for the soil characteristics. In general the coefficient of variation can be lowered by increasing the number of cores taken. The number of samples that are ultimately taken should be a good compromise between the desired expenditure, labour and time on one hand and desired level of precision on the other. Gelderman et al., 2006 developed a zigzag path soil sampling pattern which is currently widely used and accepted across most regions in sub-Saharan Africa (Fig 6.1.4.1)

In this model, samples are taken along a zigzag path forming a letter “W” on flat fields. In fields that have a rectangular shape, cores may be taken along a transect formed diagonally between the two sides of the field. In other cases where fields are uniform in topography cores are made on randomized quadrants. For fields that vary in topographical features, a multistage sampling strategy using topographical stratification may be adopted.

<table>
<thead>
<tr>
<th>Soil Sampling depths (cm)</th>
<th>0 - 10</th>
<th>10 - 20</th>
<th>20 - 50</th>
<th>60 - 80</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 15</td>
<td>10 - 20</td>
<td>30 - 50</td>
<td>60 - 100</td>
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<tr>
<td>0 - 20</td>
<td>15 - 25</td>
<td>40 - 60</td>
<td>70 - 90</td>
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<tr>
<td>0 - 30</td>
<td>15 - 30</td>
<td>40 - 70</td>
<td>70 - 100</td>
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<td>0 - 45</td>
<td>20 - 30</td>
<td>50 - 70</td>
<td>95 - 150</td>
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<tr>
<td>0 - 60</td>
<td>20 - 40</td>
<td>100 - 150</td>
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</tr>
</tbody>
</table>

*Source: Kenya Soil Health Consortium database*
Sampling for within-farm variability
Smallholder farmers in Kenya are known to apply nutrients variably within the farm. For example farmers apply manure to fields close to homestead because it is bulky while fertilizer applications are made further afield. The goal for within-farm sampling is to determine the nutrient, salt, and pH variability of fields within a farm. Once this is determined, the nutrients are mapped and fertilizer and/or lime are variably applied field-wise. This is used mainly for specific field recommendations.

Grid sampling
The field is divided into rectangular grids and a sample is taken from each grid. Each grid sample is usually a composite of 6 to 8 cores. In some procedures the cores may be taken in a “point,” usually from a circle of 6 to 8 feet around the point located in the grid of interest. If this system is used the points should be staggered in the grid as one goes from one grid to the next. This can be combined with inclusion of GPS coordinates that supports mapping of the field characteristics. Because of past management practices “streaks” of higher nutrient concentrations can often be found from one end of the field to the other. Staggering the point samples can avoid bias in the soil tests.

A number of studies have determined that the largest grid size that will adequately measure nutrient variability for a field should be no more than 2.5 acres in size. In fact, many studies have shown the size should be less than one acre. This is cost prohibitive in most situations, and many workers have found that the nutrient variability within a grid may be as high as that within the whole field. Consider using a grid system where the field history is unknown, the non-mobile nutrients (P, K, Zn) are of primary importance and are high either from past fertilization or manure applications, where small fields have been merged into one or more large fields, or where year to year variability in non-mobile nutrient tests are high.

Sampling by landscape/topography
One of the oldest procedures used to divide fields into variable nutrient zones is sampling by visual landscape differences (Fig 6.1.4.3.). Perhaps uplands are one sample, slopes another, and bottom ground another. Logically, this makes sense in that you would expect that sloped, eroded areas should have less nutrients than the bottom ground where soil and nutrients are deposited. Nutrient concentration is highest in the bottom ground followed by the middle ground (flat part of the farm) and least at the top ground (most eroded).

6.1.5 Frequency of sampling
For most field cropping systems, sampling and testing the soil in each field at least once every three years is adequate. Soil pH and nutrient levels are more stable in soils with higher cation exchange capacities (CEC). In sandy soils, with CECs below 6 meq/100g the potassium, magnesium and calcium levels may change more rapidly because of crop uptake and possible leaching. In these soils, sampling more frequently is recommended. Sampling the entire farm at one time is a good practice because it provides an evaluation of the whole farm fertility program at a given point in time. This may not always be practical. For large farm operations sampling and testing one third of the acreage each year is an alternative that provides continuity over time. For intensive cropping systems where large amount
of fertilizers may be applied annually, or crop removal may be high, annual soil testing enables the grower to maintain stable soil fertility conditions. This is especially important for many of the vegetable crops that are grown on sandy soils.

6.1.6 Soil sample processing
Most of the soil test methods require that soils are

Drying and sieving
Majority of the soil testing procedures are done on dry soils. Composite soil samples are oven dried at 40°C to a constant weight. The samples are then ground to pass through a 2 mm sieve and roots or pieces of gravel removed. Sub-sample the soil randomly and obtain a sample of 350 g and store in a clearly labeled bag in a dry place. Some samples can be taken from these samples

Post drying care
After drying, the samples are transferred to the
preparation room which is separate from the main laboratory. Air dried samples are ground with a wooden pestle and mortar so that the soil aggregate are crushed without breaking the soil particles. Samples of heavy clay soils may have to be ground with an end runner grinding mill fitted with a pestle of hard wood and rubber lining. Pebbles, concretions and stones should not be broken during grinding. After grinding, the soil is screened through a 2 mm sieve.

**NB:** The practice of passing only a portion of the ground sample through the sieve and discarding the remainder is erroneous. This introduces bias in the sample as the rejected part may include soil elements with differential fertility. The entire sample should, therefore, be passed through the sieve except for concretions and pebbles of more than 2 mm. The coarse portion on the sieve should be returned to the mortar for further grinding.

Repeat sieving and grinding till all aggregate particles are fine enough to pass through the sieve and only pebbles, organic residues and concretions remain out. If the soil is to be analyzed for trace elements, containers made of copper, zinc and brass must be avoided during grinding and handling. Sieves of different sizes can be obtained in stainless steel. Aluminum or plastic sieves are useful alternative for general purposes. After the sample is passed through the sieve, it must be mixed thoroughly. The soil samples should be stored in cardboard boxes in wooden drawers. These boxes should be numbered and arranged in rows in the wooden drawers, which are in turn fitted in a cabinet in the soil sample room.

**Sample handling in the laboratory**

As soon as the samples are received at the soil testing laboratory, they should be checked against the accompanying information sheet. Identification details should be logged in into laboratory sample logging system or entered into a laboratory sample register and each sample given a laboratory identification number in addition to sample number.

Things to note about effects of Drying of soil samples

Oven-drying at temperatures higher than 40° C can cause profound changes in chemical and biological characteristics of the sample. For example:

- Whereas drying has negligible effect on total N content, the nitrate-N content in the soil changes with increase in temperature. It is for this reason that samples for nitrate measurement have to be preserved at low temperatures that restrict microbial activity.
- Microbial population is affected due to drying at high temperature.
- With excessive drying, soil potassium may be released or fixed depending upon the original level of exchangeable potassium.

Exchangeable potassium will be increased with increasing temperatures if its original level is less than 1 meq/100 g soil (1 cmol/kg) and vice-versa. However, the effect depends upon the nature of clay mineralogy.

**Sampling of salt affected soils**

Salt affected soils may be sampled in two ways.

1. **Surface soil sampling:** Surface samples should be taken in the same way as for soil fertility analysis. These samples are used to determine gypsum requirement of the soil.
2. **Depth-wise sampling:** For reclamation purpose, it is necessary to know the characteristics of lower soil depth as well. Such soils are, therefore, sampled depth wise up to one meter. The samples may be taken from one or two spots per 0.4 hectare if the soil is uniformly salt affected. If patches are conspicuous then all big patches should be sampled separately. Soil is sampled depth wise separately (about ½ kg from each depth) for 0-15 cm, 15-30 cm, 30-60 cm and 60-100 cm soil depths. If a stony layer is encountered during sampling, such a layer should be sampled separately and its depth noted. Other procedures are as explained above.

**6.1.7 Plant sampling for analysis**

The amount of sample to be collected and the proper sample container type (e.g., glass or plastic), preservative, and storage requirements are dependent on the matrix being sampled and the parameter(s) of interest. Plant tissue preservation, containers, handling and storage instructions may require wet ice (4° C), dry ice, or liquid nitrogen.

**Leaf area index (LAI)**

Leaf area is one of the most important bio-meteorological variables to be characterized. In general, Leaf Area Index is the amount of one-sided leaf area per unit area of ground. It is an inventory of the population of leaves that are absorbing light and momentum and are exchange heat, moisture,
CO2 and trace gases with the atmosphere. LAI-2200C Plant canopy analyser uses a non-destructive method that easily and accurately measure Leaf Area Index. It consistently outperforms other methods such as Ceptometry and Hemispherical Photography in terms of flexibility, advanced features, accuracy, and ease of use.

**Chlorophyll measurement (Spad meter, green seeker)**

Determination of chlorophyll content in leaf tissue is a method used to determine the photosynthetic fitness of a plant. This method may be most useful in certain cases of metal contamination.

**Photosynthetic Capacity Measurement using In Vivo Chlorophyll Fluorescence**

The procedure involves attaching clips called “dark-adapting cuvettes” to the leaves of the plants. Adapting the leaves to darkness essentially brings the chlorophyll molecules in all the plant tissues to a baseline state so that valid comparisons can be made. After dark adaptation, light from a light source is introduced to the tissue through the cuvette by a fiber optic cable. The chlorophyll molecules in the tissue emit fluorescent light, and the signal recorded is the fluorescence signature for that plant. This is referred to as a fluorescence induction curve. The curves can be compared between the contaminated and reference areas, and with curves published in the literature, if available. Key parameters that are calculated from the curves by the instrument’s computer can be downloaded to a personal computer for statistical analysis. This method is likely to be most useful in cases of herbicide contamination but has also shown differences between controls and plants exposed to heavy metals. There is evidence that polychlorinated biphenyls (PCBs) inhibit photosynthesis. Little work has been done concerning volatile and semi-volatile organic contaminants. Gas exchange and radioisotope tracer methods should be considered for future projects.

**Weather:** At least daily rainfall at site or within 5 km for on farm trials, and minimum and maximum temperatures within a 10 km radius should be collected.

**Yield determination**

**Maize yield measurements** Maize grain and stover yields can estimated by harvesting the four central rows (3.0 m) of 5.5 m long (16.5 m 2) leaving three guard rows on either sides and 1 m each on either ends. Within each row, two maize plants are left on either ends as guard. The maize cobs are harvested, weighed and sub-samples obtained. The sub-samples (about 0.5 kg from each plot) are oven-dried and the cobs threshed. The threshing percentage is used to estimate the maize grain yield in tones per hectare. The maize stover from the net plot is harvested, weighed and sub-samples obtained. The sub-samples of stover are chopped into smaller pieces and are then oven-dried at 70°C. The ratio of dry weight to fresh weight and plot fresh weights are used to estimate the maize stover yield in tones per hectare.

**6.2 Soil testing**

Soil testing has long been accepted as a unique tool for rational fertilizer use. Soil testing can act as a watchdog to safeguard soil quality as a whole. The major objectives of soil testing are:

i. To assess the soil fertility status and recommend suitable and economic nutrient doses through chemical fertilizers and organic manure for different crops and cropping systems.

ii. To identify the type and degree of degradation problems/ abnormalities like soil acidity, salinity, toxicity and sodicity and to propose effective remedial measures.

iii. To generate data for development of soil fertility and crop suitability maps.

iv. To study soil pollution-related aspects and to devise preventive as well as remedial measures.

v. To make continual improvement in soil and plant tissue analysis.

Soil testing is a three-step process: (1) nutrient extraction from the soil sample and analysis; (2) interpretation of test results; and (3) nutrient recommendations (Mylavarapu 2009). Each step’s procedures are specific to the inherent soil characteristics and the location of the soil, and are subject to a wide variety of factors, such as crops being grown, prior soil and nutrient management, and the soil’s physical and chemical properties. Therefore, it becomes important to consider all of these factors carefully when choosing an appropriate chemical extractant for soils in a region.

**6.2.1 Soil Physical characteristics**

**Soil Texture**

Soil texture which is often referred to as particle size distribution is a stable soil characteristic which influences physical and chemical properties of the soil. The soil texture provides information about water flow potential,
water holding capacity and fertility potential among others. Water dynamics and aeration in soil are highly dependent on texture and structure and the latter are therefore important for plant growth both directly, but also through the regulation of microorganisms – the engine in decomposition and nutrient cycling processes (Stenberg, 1999). Soil texture is dependent on the mixture of different particle size grades and refers to the relative portion of the various size groups of the various particles in the soil. From largest to smallest the soil grades are:

- Gravel and pebbles > 2.0 mm
- Coarse sand: 0.2 -2.0 mm diameter
- Fine sand: 0.02 – 0.2 mm diameter
- Silt: 0.002– 0.02 mm diameter
- Clay: < 0.002 mm diameter

For soil texture, most focus has been on clay content because it has a large influence on structure through promotion of formation of soil aggregates and its swelling and shrinking properties forming cracks. Soil texture can be assessed in the laboratories by determining percentages of sand, silt, and clay particles. These percentages are used on the textural triangle to determine the textural class. Soil particles remain aggregated due to various types of binding forces and factors which include the content of organic matter, colloidal substances present in the soil, oxides of iron and aluminum and the hydration of clay particles. To estimate the content of various sizes of soil particles, the soil sample has to be brought into a dispersed state by removing various types of binding forces using a dispersant such as Calgon (Sodium hexametaphosphate). In the dispersed soil samples, the soil particles settle down at a differential settling rate according to their size as explained by Stokes law (1851). The law stipulates that the resistance offered by the liquid to the fall of the particle varies with the radius of the sphere and not with the surface.

Generally, two methods are most commonly used for estimation of particle size or soil texture:

1) Pipette method
2) Hydrometer method

Calculation of soil particle size distribution

11 % sand (grams of sand that settles within 40 seconds ÷ Soil weight) × 100
12 % clay (grams of correlated to hydrometer at the end of 2 hours ÷ Soil weight) × 100
13 % silt (find the silt by difference. Subtract the sum of the percent sand and clay from 100).

The calculated ratios of different particles are plotted on the textural triangle to determine the textural class (Figure 6.2.1).

- Each side corresponds to the percentage of soil separate.
- The blue arrow represents the direction in which one reads the clay separate, the pink arrow corresponds to the sand separate and the orange arrow corresponds to the silt separate.

**Soil texture determination by feel**

With experience it is possible to determine the soil texture by feeling it between the thumb and the first finger when it is wet. This is illustrated in fig 5 below.

### 6.2.2 Soil Structure:

This is the combination or arrangement of primary soil particles (sand, silt and clay) into secondary particles, units or granules. These secondary particles, granules or units are called aggregates and are composed of many primary soil particles held together by organic substances, iron oxides, carbonates, clays and/or silica. The natural aggregates are called peds.

**Soil Structural Classes:**

Soil structural units or peds are described by three characteristics: type (shape), class (size) and grade (strength of cohesion). Structural types describe the shape of the ped with the terms: angular blocky, sub-angular blocky, columnar, granular, platy and prismatic being used. Structural classes are the ped sizes such as very fine, fine, medium, coarse (or thick) and very coarse (or very thick). Structural grades are evaluated by the distinctness, stability or strength of the peds.

### 6.2.3 Particle Density and Bulk Density

Density is the mass of an object per unit volume. Water is a reference for density measurements; that is, other materials are often compared to the density of water. In the metric system, water weighs one gram per cubic centimetre which is a convenient number. The mineral soil densities are greater than the density of water; organic soil densities are less than that of water.

Particle density is the density of the solid soil particles only. The measurement does not include water weight or pore (air) space. The dominant soil minerals (quartz,
Figure 6.2.1: Soil textural triangle

feldspars, micas, and clay minerals) density average about 2.65g/cm³ (2650kg/m³), the standard value used in calculations if particle density is not measured. Bulk density is the density for a volume of soil as it exists naturally. It includes any air space and organic materials in the soil volume. Since bulky density is calculated for the dried soil, moisture is not included in the sample weight. The bulk soil volume is assumed not to have changed by drying; only the water has been removed, leaving empty pores. Thus a loosened soil with an increased total pore space will have a smaller weight per unit volume than the same soil after it is compacted. Hence bulk density can be used to estimate differences in compaction of a given soil, such as might result after tillage with heavy equipment on a wet clay soil. For good plant growth, bulk densities should be below 1.4g/cm³ for clays and 1.6g/cm³ for sands. Generally bulk density is used to calculate total water storage capacity per soil volume and to evaluate soil layers to determine if they too compacted to allow root penetration or adequate aeration.

Measurement of soil bulk density

The bulk density of soil is measured by taking an undisturbed block of soil (clod or soil core), determining its volume, drying it and weighing it. Clods can be coated with paraffin or liquid plastic and dipped into water to measure water displacement, and hence to calculate volume. When soil cores are taken by a metal cylinder, the exact volume is determined by measuring the cylinder volume. The formula for bulk density is:

\[
\text{Bulk density} = \frac{\text{Soil mass oven-dry}}{\text{Soil volume}}
\]

The average weight of soil for a hectare (or acre) area per unit depth is calculated by multiplying the soil volume by its bulk density. A hectare - 15 cm or acre-furrow-slice weight is estimated for bulk density of about 1.3g/cm³ (1300 kg/m³). A hectare -15 cm volume of soil of bulk density of 1300kg/m³ would weigh approximately 2,000,000 kg when oven dry.
Figure 6.2.2: Guide for estimating soil texture using the feel method (Thien S., 1979)

Place 25-50 g soil in palm. Add water slowly and knead soil to wet all aggregates. Soil is at the proper consistency when plastic and moldable, like moist putty.

- Does soil remain in a ball when squeezed? 
  - Yes → Add more dry soil.
  - No → Is soil too dry?
    - Yes → SAND
    - No → Is soil too wet?
      - Yes → SAND
      - No → Does the soil form a ribbon?
        - No → Does gritty feeling predominate?
          - Yes → LOAMY SAND
          - No → SILT
        - Yes → Does soil make a ribbon 2.5 cm or less before breaking?
          - Yes → Excessively wet a small pinch of soil in palm and rub with forefinger
          - No → Does soil make a ribbon 2.5-5 cm before breaking?
            - Yes → Excessively wet a small pinch of soil in palm and rub with forefinger
            - No → Does soil make a ribbon 5 cm or longer before breaking?
              - Yes → Excessively wet a small pinch of soil in palm and rub with forefinger
              - No → SANDY LOAM

SANDY LOAM
- Does gritty feeling predominate?
  - Yes → SANDY CLAY LOAM
  - No → SILT LOAM
- Does smooth feeling predominate?
  - Yes → SILTY CLAY LOAM
  - No → Silt

SILT LOAM
- Does smooth feeling predominate?
  - Yes → SILTY CLAY
  - No → CLAY LOAM

SANDY CLAY LOAM
- Does gritty feeling predominate?
  - Yes → SANDY CLAY
  - No → CLAY LOAM

SANDY CLAY
- Does gritty feeling predominate?
  - Yes → CLAY
  - No → LOAM

SILTY CLAY LOAM
- Does smooth feeling predominate?
  - Yes → SILTY CLAY
  - No → CLAY LOAM

SILTY CLAY
- Does smooth feeling predominate?
  - Yes → CLAY
  - No → LOAM

LOAM
- Does gritty feeling predominate?
  - Yes → LOAM
  - No → CLAY

CLAY
6.3 Soil Porosity and Permeability

Pore spaces (also called voids) in a soil consist of that portion of the soil volume not occupied by solids, either mineral or organic. Permeability is defined as the quality of a soil that enables water or air to move through it. Pores in soil are the result of irregular shapes of primary particles and their aggregation; the forces of penetrating roots, worms and insects; and of expanding gasses entrapped by water. Under field conditions, pore spaces are occupied at all times by air and water. Tortuous pathways best describe soil pores. Soil particles have irregular shapes and thus leave the spaces or pores between them very irregular in size, shapes and direction. Sands have large and continuous pores. In contrast, clays, although containing more total pore space because of minute size of each clay particle, have small pores, which transmit water slowly. Small bottlenecks in the pores fill with water and block air movement through them. Air exchange may be inadequate for plant root growth in some clayey soils. The most rapid water and air movement is in sands and strongly aggregated soils, whose aggregates act as sand grains and pack to form many large pores.

Pores are described according to their average diameter in millimetres as follows:
- Very fine: < 0.5
- Fine: 0.5 – 2
- Medium: 2 – 5
- Coarse: > 5

The percentage of a given volume of soil occupied by pore spaces is called Porosity and may be calculated from the formula:

\[ \text{Porosity} = \frac{\% \text{ pore space}}{100\% - \% \text{ solid space}} \]

6.3.1 Soil Water

Soil moisture content is defined as the water that can evaporate from the soil to a constant weight upon heating to 105°C for approximately 48 hours. There are three forms of soil moisture namely: liquid water which is held in transmission and retention pores, absorbed water held by the forces of cohesion and adhesion on the soil particles and strongly absorbed water which is held within the lattice structure of clay mineral. Two important aspects of the liquid water held within the pores are field moisture capacity and permanent wilting point. The difference in moisture content between field capacity and permanent wilting point is the available water capacity. Different soil textures have different soil water capacity (Table 6.3.1)

\[ \text{AWC} = \text{Fc} - \text{Wp} \]

Crops require water to complete their life cycle and below are some examples of water requirements.
- Low (<400mm): Millet, Sorghum, Maize, Sudan grass, etc.
- Medium (400 - 700mm): Potatoes, Wheat, Barley, Soybeans, etc.
- High (>700mm): Clover, Sugarcane, Banana, Lucerne, etc.

Water is required for all life. In soils, water is supplied to plants through the roots, it lubricates the soil allowing root penetration, it is necessary for microbial mobility and action and it allows nutrients mobility. In a dry portion of the soil water uptake by plants stops, nutrient absorption essentially ceases and the root growth practically stops.

Obvious questions about soil water are these:
1) How is water held in a soil?
2) What determines how much water a soil holds?
3) Can plants use all the water in a soil?

Water entry into soils (infiltration) is too fast in sands and too slow in clays for optimum crop production. Inadequate air exchange will occur in the small and water filled pores in clay soils. Sandy soils hold low plant available amount of water following wetting. Thus, sands will require frequent rains or irrigations to supply adequate water to plants. Clay soils will have slow drainage of excess water; sandy soils will be well drained if drainage is possible.
The soil is very important to the plant as a water reservoir to supply the plant’s water daily or even weeks between rains or irrigations.

### 6.3.2 Water Retention Forces in Soils
Soil serves as a water reservoir but a leaky one. When too much water is added to a soil, the excess runs off over the surface or into deeper layers. Why does the soil hold some of the water, yet allow part of it to drain deeper? Water is held in soils because of the attraction between unlike charges – a positive ion attracted to a negatively charged ion (see figure below). The positively charged hydrogen atoms of water are attracted to nearby negatively charged ions, such as oxygen, even to the oxygen of another adjacent water molecule. Most soil minerals are composed of 70 – 85 percent by volume of negatively charged oxygen atoms. Positively charged hydrogen atoms of water bond strongly to these surface oxygen atoms by adhesive bonding (the attraction of unlike charged molecules). The hydrogen atoms of water are also attracted (bonded) to oxygen atoms of other water molecules, including those already adsorbed to the soil particle surfaces. The attraction of like molecules for each other is cohesive bonding. Such bonding between two molecules through a single hydrogen atom is called hydrogen bonding (H bonding).

Strong combined adhesion and cohesion forces cause water films of considerable thickness to be held on the surfaces of soil particles. Because the forces holding water in soil are surface - attractive forces, the more the surface (the more clay and organic matter) a soil has, the greater is the amount of water adsorbed.

To indicate the strength with which water is held in a soil, several concepts have been used. The concept of pressure:- the pressure required to force the water off the soil – was used in early studies and was measured in atmospheres of pressure needed to remove water from a soil. The opposite of pressure:- moisture suction

<table>
<thead>
<tr>
<th>Texture</th>
<th>Range</th>
<th>Average AWC (mm/m)</th>
<th>Days (ET= 8 mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse sand</td>
<td>50-70</td>
<td>60</td>
<td>8</td>
</tr>
<tr>
<td>Fine sand</td>
<td>75-95</td>
<td>85</td>
<td>11</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>90-110</td>
<td>100</td>
<td>13</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>105-125</td>
<td>115</td>
<td>14</td>
</tr>
<tr>
<td>Fine sandy loam</td>
<td>120-140</td>
<td>130</td>
<td>16</td>
</tr>
<tr>
<td>Very fine sandy loam</td>
<td>130-150</td>
<td>140</td>
<td>18</td>
</tr>
<tr>
<td>Clay and clay loam</td>
<td>120-180</td>
<td>150</td>
<td>19</td>
</tr>
<tr>
<td>Silt clay and silt clay loam</td>
<td>140-180</td>
<td>160</td>
<td>20</td>
</tr>
<tr>
<td>Silt loam</td>
<td>160-210</td>
<td>185</td>
<td>23</td>
</tr>
<tr>
<td>Peats and mucks</td>
<td>160-250</td>
<td>210</td>
<td>26</td>
</tr>
</tbody>
</table>

ET – Evapo-transpiration

---

**Table 6.3.1: Soil available water capacity of different textural classes (Lal and Shukla 2004)**

Fig 6.3.2.1: Water Molecule
or tension - has also been used and was measured in atmospheres of suction or tension. Currently soil water potential is used. It is defined as the work the water can do when it moves from its present state to a pool of water in the defined reference state. Soil Water potential (also known as matric potential), is the ability of pure water to do work and is usually measured in bars, Pascals (Pa) or Joules/kg. (1 bar = 100 kPa = 100 J/kg). 1 kPa = 1000 Pa.

6.3.3 Energy Classification for Soil Water
As defined above soil water potential refers to work and therefore and energy term and not a pressure term. Adsorbed water in soils is less free to move than is water in a pool of water (which has zero potential by definition). Thus soil water has less free energy (less ability to do work than does water in a pool). The free energy value of less than zero is indicated by a negative sign. Negative free energy means that work must be done on the water to remove it from the soil to a pool of water. The more tightly water is held the more negative is the number.

The soil water potential is a combination of the effects of the surface area of soil particles and small pores that adsorb water (also known as matric potential), the effects of dissolve substances (solute or osmotic potential) and the atmospheric or gas pressure effects (pressure potential). In non-salty well-drained soil, the matric potential is almost equal to the water potential. An additional effect of the position of the water (such as being elevated) compared to the reference state (the reference free-energy state = 0 and is at specified elevation) is called the gravitational potential. Gravitational potential is not related to soil properties, only to the water’s elevation in comparison to a reference position. These potentials are defined or interrelated to the following symbols:

\[ \psi_t = \psi_m + \psi_s + \psi_p + \psi \]

Where \( \psi_t \) = total soil water potential
\( \psi_m \) = matric potential
\( \psi_s \) = solute potential
\( \psi_p \) = pressure potential

Matric potential (\( \psi_m \)) is the dominant portion (about 95% or more) of the total water potential (\( \psi_t \)) in most situations.

Water from irrigation or rainfall moves into and through saturated soil by gravity flow, often very rapidly. Lower water movement, in all directions, occurs when the soil is not saturated and because of the forces (other than gravitational forces) holding the water. Water flows from areas of high water potential (usually wetter soil) to low water potential (usually drier soil).

The water potential in a soil varies. Water that is adjacent to soil particle surfaces has a lower (more negative) potential (e.g., -800 MPa) than has water on the outside portion of thick water films (which might have a potential of about -10 to -30 kPa almost loosely enough for gravitational flow). Note that water is held more tightly as the negative value increases in magnitude.

Soil Water Retention Curve
Soil water retention curve also referred to as a soil water characteristic (SWC) curve describes the amount of water retained in a soil (expressed as mass or volume water content, \( \theta_m \) or \( \theta_v \)) under equilibrium at a given matric potential. A SWC is an important hydraulic property related to size and connectedness of pore spaces; hence strongly affected by soil texture and structure, and by other constituents including organic matter. Modeling water distribution and flow in partially-saturated soils requires knowledge of the SWC, therefore plays a critical role in water management and in prediction of solute and contaminant transport in the environment. Typically a SWC is highly nonlinear and is relatively difficult to obtain accurately. Because the matric potential extends over several orders of magnitude for the range of water contents commonly encountered in practical applications, the matric potential is often plotted on a logarithmic scale. Figure 6.3.3.1 depicts representative SWC curves for soils of different textures, demonstrating the effects of porosity (saturated water content) and the varied slopes of the relationships resulting from variable pore size distributions.

6.3.4 Water Flow through Soil
Most rapid water movement in soils is through large pores and is caused by gravity pull. This water moves at water potential lager (less negative) than -33 kPa and is called saturated flow.

Unsaturated flow occurs when the gravitational force is no longer strong enough to cause flow. The other forces of matric and osmotic potentials predominate at water potentials lower (more negative) than -33 kPa. Water
flow in the soil then is in any direction.

Saturated Flow
Saturated flow is water flow through the soil caused by gravity’s pull. It begins with water infiltration, which is water movement into the soil when rain or irrigation water is on the soil surface. When the soil profile is wetted, the movement of more water flowing through the wetted soil is termed percolation. It is percolating water moving through the soil and substrata, which carries away the nutrients and other salts dissolved from the soil.

The most common mathematical expression for the vertical water flow rate through a soil is called Darcy’s law. The law states that the rate of flow \( Q_w \) increases with depth of water and the soil area through which it flowed. The flow decreases with an increased depth of the soil \( ds \) through which the water flowed. Since each soil has a different combination of pore sizes and numbers of pores, each soil has a different flow rate constant \( K \). Because the flow is downwards and water thus loses potential (work must be done to put the water back where it started flowing from), the values are negative. Darcy’s equation may thus be written as:

\[
Q_w = - K \frac{(dw)At}{ds}
\]

Where \( Dw = \) water quantity, \( cm^3 \), \( K = \) rate constant, \( cm/s \), \( dw = \) water height (head), \( cm \)

Or

\[
K = - \frac{Q_w(ds)}{At(dw)}
\]

Where \( A = \) Soil area, \( cm^2 \), \( t = \) time, \( ds = \) soil depth used, \( cm \)

Water infiltration is rapid into large continuous pores in the soil. It is reduced by anything that decreases either the size or amount of pore space or wettability such as structure breakdown, pore clogging by lodged soil particles and the slower movement of water deeper water as it reaches denser subsoil.

Unsaturated flow
This is the flow of water held with water potentials lower (more negative) than about -20 to -33 kPa. Water will move towards the region of lower potential (towards...
the greater pulling force). In a uniform textured and structured soil this means that water moves from wetter to drier areas. The water movement may be in any direction. The rate of flow is greater as the water potential gradient (the difference in potential between wet and dry) increases and as the size of water-filled pores also increases.
7.0 Soil Acidity

7.1 Soil pH
Soil pH is a measure of the relative acidity or alkalinity in soils. It is a fundamental chemical property because it influences the availability of nutrients and the solubility of elements like aluminum and manganese, which are detrimental to crop growth.

The desirable pH range for optimum plant growth varies with crops. While some grow best within the 6.0 to 7.0 pH range, others grow well under more acidic conditions. Soil pH may be attributed to various factors including mineralogy, climate and management of soils. Although some soils may have the desirable pH for the crop being grown, others require amendments such as lime to increase or sulfur to lower pH.

By definition soil pH is the inverse logarithm of the hydrogen ion concentration. Soil pH controls the form, solubility and availability of many plant nutrients (Fig.7.1.). At low soil pH soil fixes certain nutrients such as phosphorus making them unavailable for crop growth. A soil with a pH lower than 7.0 is an acid soil and one with a pH higher than 7.0 is alkaline. The soil must be adjusted to suit the plant which will occupy that area if it is not already within that plants requirement range.

Correlation between pH in water, CaCl₂, KCl
Soil pH is one of the most important chemical properties used as an index in soil management for crop production. It measures the H⁺ ion activity in the soil solution. A number of methods have been used in most laboratories to measure soil pH electronically: soil/water slurries of

1:1 or 1:3 (vol/vol) and allow them to stand for 1 hr or less before reading, 0.01 M CaCl₂ and KCl. pH values of soils in 0.01 M CaCl₂ tend to be slightly lower than, but highly correlated with those in water. The lower value
of pH in a CaCl$_2$ solution is related to the displacement of H$^+$ and Al$^{3+}$ ions from exchange sites by Ca$^{2+}$. pH values measured in water, 0.01 M CaCl$_2$, and 0.1 M KCl at dilution ratios of 5:1, 2.5:1 and 2:1 (solution : soil) are highly correlated. The relationship between pH in water (pH$_w$) and pH in 0.01 M CaCl$_2$ (pH$_{ca}$) at 2.5:1 solution: soil is pH$_{ca} = 1.05$ pH$_w - 0.9$. Different crops require different levels of soil pH to thrive. Some crops do well in slightly acidic soils while others in alkaline soils. Table 8.1 below presents ranges of soil pH suitable for different crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Optimal pH</th>
<th>Crop</th>
<th>Optimal pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>5.8-6.2</td>
<td>Wheat</td>
<td>6.3-6.5</td>
</tr>
<tr>
<td>Beans</td>
<td>6.0-7.0</td>
<td>Peanuts</td>
<td>5.0-6.0</td>
</tr>
<tr>
<td>Barley</td>
<td>6.3-6.5</td>
<td>Soybeans</td>
<td>6.6-7.0</td>
</tr>
<tr>
<td>Avocado</td>
<td>6.0-7.0</td>
<td>Peas</td>
<td>5.6-6.6</td>
</tr>
<tr>
<td>Beet</td>
<td>5.6-6.6</td>
<td>Peppers</td>
<td>6.0-8.0</td>
</tr>
<tr>
<td>Broccoli</td>
<td>6.0-7.0</td>
<td>Potato</td>
<td>5.8-6.5</td>
</tr>
<tr>
<td>Cabbage</td>
<td>5.6-6.6</td>
<td>Pumpkins</td>
<td>5.0-7.0</td>
</tr>
<tr>
<td>Carrot</td>
<td>5.0-6.0</td>
<td>Spinach</td>
<td>5.0-7.0</td>
</tr>
<tr>
<td>Chili pepper</td>
<td>5.0-6.0</td>
<td>Squash</td>
<td>6.0-7.0</td>
</tr>
<tr>
<td>Cucumber</td>
<td>5.0-6.0</td>
<td>Strawberries</td>
<td>6.0-7.0</td>
</tr>
<tr>
<td>Eggplant</td>
<td>5.0-6.0</td>
<td>Sunflowers</td>
<td>6.0-7.0</td>
</tr>
<tr>
<td>Garlic</td>
<td>5.0-6.0</td>
<td>Sweet potatoes</td>
<td>5.0-7.0</td>
</tr>
<tr>
<td>Leek</td>
<td>5.0-6.0</td>
<td>Tobacco</td>
<td>5.0-7.0</td>
</tr>
<tr>
<td>Lettuce</td>
<td>6.5-7.0</td>
<td>Tomatoes</td>
<td>5.5-7.0</td>
</tr>
<tr>
<td>Mushroom</td>
<td>7.0-8.0</td>
<td>Turnip</td>
<td>5.0-7.0</td>
</tr>
<tr>
<td>Yam</td>
<td>6.0-8.0</td>
<td>Grasses</td>
<td>5.8-6.2</td>
</tr>
</tbody>
</table>

The standard method for determination of soil pH uses a soil: water ratio of 1:1, 1:2.5 weight to volume basis.

7.1.1 Management of soil acidity
Soil acidity is a combination of soil conditions that limit plant growth and its management requires manipulation of various soil and plant factors in favour of better growth or crop production. This management practises may vary with severity of acidity, type of soil, type of farming practices and socio-economic conditions of the farm. The common method for managing acidic soils is through liming.

7.2 Liming
Liming is a practice of adding lime material to acid soils for the purpose of increasing soil pH and maintaining a favourable soil environment for plant growth. A more favourable environment may be a consequence of the following effects
1. Desirable soil pH
2. Decreasing the toxicity of Al and Mn
3. Increasing Ca and Mg supplies
4. Enhancing availability of P and Mo
5. Improving mineralization of organic compounds thereby improving N, S and P uptake
6. Improving soil biological activities such as N fixation.

The quantity of lime added depends on the type of soil, liming material, crop species, cultivar and economic consideration. For most agronomic crops Al concentration or activity in the soil solution or Al saturation in the exchange complex is the single most important measure for assessing Al toxicity. When the Al saturation of exchange capacity exceeds 60% a significant amount of Al is dissolved in the soil solution. At this point the Al toxicity is mainly caused by soil acidity.

To adjust soil pH to a desired or target pH value, one must not only know the current soil pH but also the buffering ability of the soil to resist change in pH. Most soil testing laboratories make lime recommendations from a calibration based on measured pH before and after the addition of a pH buffer solution. The amount of soil acidity that must be neutralized by lime application is called the soil’s lime buffer capacity (LBC). It is the measure of the amount of soil acidity that must be neutralized to raise soil pH by one unit. In terms of lime,
LBC is defined as the weight of pure lime (CaCO₃), in milligrams, needed to raise the soil pH of one kilogram of soil by one unit. The pH of a mixture of soil and salt solution is measured before and 30 minutes after adding a single dose of calcium hydroxide. The value of LBC is largely determined by the difference in the two pH readings.

Soil LBC characterizes a soil’s buffering ability to resist a pH change. In simple terms, acidic soils with a high LBC would require more lime (greater resistance to pH change) than those with lower LBC. Likewise, more acid-forming amendments like sulfur are required to lower the pH of a soil with high LBC. Hence LBC varies with soil type and management. LBC is measured in ppm. In most cases it varies between 100 to 400 ppm.

\[ \text{LBC}_{30} \] refers to LBC after 30-minute equilibration whereas \[ \text{LBC}_{\text{eq}} \] refers to LBC at equilibrium at five days. Analysis of the data confirmed that the LBCEq could be predicted accurately from LBC\textsubscript{30} using either equation (a) or (b) below. The equations below represent formulas for calculation when LBC is less or more than 250 ppm.

\[
\begin{align*}
\text{a. Soils with } \text{LBC}_{30} \leq 250 \text{ ppm: } & \quad \text{LBC}_{\text{eq}} = (3.6709 \times \text{LBC}_{30}) - 188.25 \\
\text{b. Soils with } \text{LBC}_{30} \geq 250 \text{ ppm: } & \quad \text{LBC}_{\text{eq}} = \text{LBC}_{30} \times 2.90
\end{align*}
\]

(Source: Sonon et al., 2012)

### 7.2.1 Lime Requirement Calculations

The primary purpose of the LBC method is to determine the lime requirement (LR) of a soil to adjust it to the desired pH level. An LR is calculated based on three factors: 1) the soil’s initial pH, 2) the desired or target pH and 3) the soil’s LBC (in the current method, it is LBCEq). The LR is typically presented as the pounds of lime per acre needed to raise soil pH to the target value and can be calculated as shown below.

\[
\text{LR} = \text{LBC}_{\text{eq}} \times (\text{Target pH} - \text{Initial pH}) \times 2.24 \times 1.5 \times \left(\frac{20}{15}\right)
\]

The optimum for general cropping is between pH 6.0 and 6.5. For permanent grassland the optimum pH is slightly lower. There are several methods of testing the pH of soils and with some knowledge of the relationship between pH and lime requirement for various soil types the pH can be used as a guide to the lime requirement.

### Lime Requirement

Crop yields are normally high in soils with pH values between 6.0 and 7.5. Lime is added to raise the pH of acid soils, and the amount of lime required to raise the pH to an optimum level is known as Lime Requirement. A number of methods are available for the determination of lime requirement. The Woodruff and the Shoemaker et al. methods are discussed here which are based on the use of a buffer solution, whose pH undergoes change when treated with acid soils. The pH of buffer solution will gradually decrease when H⁺ ion concentration increases. When H⁺ increases by 1 meq in 100 ml buffer solution, pH value will decrease by 0.1 unit. Buffer solutions needs to be prepared afresh. A 0.05M solution of AR grade potassium hydrogen phthalate (molecular weight 204.22) gives a pH of 4.0 at 25°C and it can be used as a buffer.

### Lime application under field conditions

Lime reacts with soil only when there is adequate soil lime contact and moisture. However, liming materials are not easily soluble thus farmers should apply lime long before sowing in order to give time for lime reaction and soil pH adjustment before crop development. The period should be at least 3 to 6 weeks before planting to give a good lime reaction. Liming acid soils is usually required every three to five years, depending on several factors such as management, rainfall, soil characteristics etc. If applied too near the planting time, it can induce a temporary K deficiency because of the high calcium availability. Another factor determining the effectiveness of lime is the placement.
Effective liming rate

The reactivity of lime is related to its fineness and purity. The amount of lime that needs to be applied should be adjusted based on both these factors. The amount of lime that needs to be applied should be adjusted based on both these factors. The approach to adjust purity is best shown through an example,

\[
\frac{1 \text{ kg lime}}{1,000 \text{ kg CaCO}_3} \cdot \frac{0.85 \text{ kg CaCO}_3}{0.5 \text{ kg lime}} = 1,176 \text{ kg lime}
\]

The rates should also be adjusted for size of the liming material. If the material does not pass through a 10 mesh screen (10 wires/in.) then it will have little impact on soil pH. If the liming material passes though a 10-mesh but not a 50-mesh screen (50 wires/in.), then the amount of liming material should be doubled (table 7.2.1.).

<table>
<thead>
<tr>
<th>Lime passes through mesh size</th>
<th>Relative liming effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;50</td>
<td>100</td>
</tr>
<tr>
<td>10-50</td>
<td>50</td>
</tr>
<tr>
<td>&lt;10</td>
<td>0</td>
</tr>
</tbody>
</table>

Example:

If calculations show that 1000 kg of CaCO₃ are needed to increase the pH, how CaCO₃ should be applied if analysis shows that it is 90% pure and 25% passes through a 50 mesh screen and 75% passes through a 10-50 mesh screen.

Purity

\[
\frac{1 \text{ kg lime}}{1,000 \text{ kg CaCO}_3} \cdot \frac{0.90 \text{ kg CaCO}_3}{0.90 \text{ kg lime}} = 1,111 \text{ kg lime}
\]

Solution:

Effective:

\[
\frac{1 \text{ effective lime}}{0.5 \text{ effective lime}} + \frac{0.75 \cdot 1 \text{ actual lime}}{1 \text{ actual lime}} = 0.625 \text{ effective lime}
\]

Lime needed:

\[
\frac{1 \text{ kg lime}}{1,111 \text{ kg CaCO}_3} \cdot \frac{0.625 \text{ effective lime}}{0.625 \text{ effective lime}} = 1,778 \text{ kg lime}
\]

Liming materials

Commonly used materials for liming acid soils include calcium carbonate, calcitic limestone, dolomitic limestone, calcium hydroxide, calcium oxide etc (table 7.2.2).

The speed and degree of reaction are determined by fineness of grind and placement in the soil. Lime is not very soluble in water, so it must be finely ground to effectively neutralize soil acidity. The finer the particle sizes the faster the acid neutralizing rate.

The benefits of liming include:
- Improves soil physical, chemical and biological conditions
- Increases root proliferation and promotes above-ground crop growth to improve nutrient and water uptake
- Enhance nutrient use efficiency by as much as 50% enhancing profitability.
Table 7.2.1.2: Acid neutralizing values for different materials used to manage soil acidity

<table>
<thead>
<tr>
<th>Lime material</th>
<th>Calcium carbonate equivalent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium carbonate</td>
<td>100</td>
</tr>
<tr>
<td>Calcitic limestone</td>
<td>85 to 100</td>
</tr>
<tr>
<td>Dolomitic limestone</td>
<td>95 to 108</td>
</tr>
<tr>
<td>Marl (Selma chalk)</td>
<td>50 to 90</td>
</tr>
<tr>
<td>Calcium hydroxide (slaked lime)</td>
<td>120 to 135</td>
</tr>
<tr>
<td>Calcium oxide (burnt or quick lime)</td>
<td>150 to 175</td>
</tr>
<tr>
<td>Calcium silicate</td>
<td>86</td>
</tr>
<tr>
<td>Basic slag</td>
<td>50 to 70</td>
</tr>
<tr>
<td>Ground oyster shells</td>
<td>90 to 100</td>
</tr>
<tr>
<td>Cement kiln dusts</td>
<td>40 to 100</td>
</tr>
<tr>
<td>Wood ashes</td>
<td>40 to 50</td>
</tr>
<tr>
<td>Power plant ashes</td>
<td>25 to 50</td>
</tr>
<tr>
<td>Gypsum (land plaster)</td>
<td>None</td>
</tr>
</tbody>
</table>

Source: Soil acidity evaluation, IPNI, 2013

7.2.2. Soil Electrical Conductivity (EC) and Gypsum requirement

The soils having pH value more than 8.0-8.5 may have the following special features:

- Presence of excessive amounts of soluble salts.
- Presence of excessive amounts of sodium on the exchange complex.

Such soils are generally not considered suitable for growing most of the crops unless treated with suitable amendment materials. However, there are salt tolerant crops which could be grown on these soils. To determine the quality of these soils, the following estimations are required:

- pH (as described before)
- Salt content or electrical conductivity
- Exchangeable sodium or gypsum requirement

Table 7.2.2.1: Chemical characteristics of saline, non-saline sodic and saline sodic soils

<table>
<thead>
<tr>
<th>Soil</th>
<th>EC (dS/m)</th>
<th>Exchangeable</th>
<th>Sodium Percentages (ESP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline</td>
<td>&gt;4.0</td>
<td>&lt;15</td>
<td>&lt;8.5</td>
</tr>
<tr>
<td>Sodic (non-saline)</td>
<td>&lt;4.0</td>
<td>&gt;15</td>
<td>&gt;8.5</td>
</tr>
<tr>
<td>Saline Sodic</td>
<td>&gt;4.0</td>
<td>&gt;15</td>
<td>&lt;8.5</td>
</tr>
</tbody>
</table>

Source: Richards, 1954

7.3 Cation exchange capacity (CEC)

The cation exchange capacity is the sum total of exchangeable cations that a soil can absorb expressed in centimoles per kilogram or in milliequivalents/100 g of soil. Cation exchange capacity in soil is a reversible chemical reaction and corresponds to the negative charge of the soil. The principal factors which determine CEC are the amount and the type of clay present, the organic matter content, and the soil pH. Representative CEC values of common exchange materials in soils at pH 7.0 are organic matter 200-400 meq/100g, vermiculite 100-150 meq/100g, montmorillonite 60-100 meq/100g, illite 20-40 meq/100g, kaolinite 2-16 meq/100g and sesquioxides 0 meq/100g. The cation exchange capacity is commonly determined as the quantity of cations absorbed from the salt solution buffered at pH 7 with NH4OAc or at pH 8.2 with BaCl2-triethanolamine. This method is not suitable for tropical soils that exhibit a significant amount of variable charge or for temperate soils with significant organic matter content. The measurement that reflects more accurately, the total charge at the actual soil pH involves leaching with a neutral un-buffered salt, such as KCl or CaCl2, determined at the pH of the soil, which is called the effective CEC. Cation exchange capacities obtained using this method has lower values than those obtained by other methods. A minimum value of 4 cmol/kg is needed to retain most cations are susceptible to leaching. For acid soils, the CEC can be increased through addition of organic matter or lime.
Table 72.2.2: General interpretation of EC values

<table>
<thead>
<tr>
<th>Soil EC (mS/cm)</th>
<th>Crop reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Salt free 0-2 &lt; 0.15</td>
<td>Salinity effect negligible, except for more sensitive crops</td>
</tr>
<tr>
<td>2. Slightly saline 4-8 0.15-0.35</td>
<td>Yield of many crops restricted</td>
</tr>
<tr>
<td>Moderately saline 8-15 0.35-0.65</td>
<td>Only tolerant crops yield satisfactorily</td>
</tr>
<tr>
<td>4. Highly saline &gt;15 &gt;0.65</td>
<td>Only very tolerant crops yield satisfactorily</td>
</tr>
</tbody>
</table>

The CEC is calculated using the equation given below:

\[ \text{CEC} = \sum (\text{Ca, Mg, K, Na, H, Al}) \text{ in cmolc/kg} \]

7.4 Base saturation

Percent Base Saturation

Percent base saturation (BS) is the percentage of the CEC occupied by the basic cations Ca\(^{2+}\), Mg\(^{2+}\) and K\(^{+}\). Basic cations are distinguished from the acid cations H\(^{+}\) and Al\(^{3+}\). At an approximate soil pH 5.4 or less, Al\(^{3+}\) is present in a significantly high concentration that hinders growth of most plant species, and the lower the soil pH, the greater the amount of toxic Al\(^{3+}\). Therefore, soils with a high percent base saturation are generally more fertile because:

1. They have little or no acid cation Al\(^{3+}\) that is toxic to plant growth.
2. Soils with high percent base saturation have a higher pH; therefore, they are more buffered against acid cations from plant roots and soil processes that acidify the soil (nitrification, acid rain, etc.).
3. They contain greater amounts of the essential plant nutrient cations K\(^{+}\), Ca\(^{2+}\) and Mg\(^{2+}\) for use by plants.

The percentage base saturation is expressed as follows:

\[ \%\text{BS} = \left[ \frac{(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^{+})}{\text{CEC}} \right] \times 100 \]

Depending on soil pH, the soil’s base saturation may be a fraction of CEC or approximately equal to CEC. In general, if the soil pH is below 7, the base saturation is less than CEC. At pH 7 or higher, soil clay mineral and organic matter surfaces are occupied by basic cations, and thus, base saturation is equal to CEC. Figure 2 illustrates the relative amount of cations retained on soil surfaces at various soil pH levels.

7.4.1 Significance of CEC and BS

A soil’s CEC affects fertilization and liming practices. For example, soils with high CEC retain more nutrients than low-CEC soils. With large quantities of fertilizers applied in a single application to sandy soils with low CEC, loss of nutrients is more likely to occur via leaching. In contrast, these nutrients are much less susceptible to losses in clay soils.

Crop production releases acidity into soil. Soil pH will decrease more due to crop production on low CEC soils. High CEC soils are generally well buffered such that pH changes much less from crop production. Therefore, sandy soils low in CEC need to be limed more frequently but at lower rates of application than clay soils. Higher lime rates are needed to reach an optimum pH on high CEC soils due to their greater abundance of acidic cat\textsuperscript{ions} at a given pH.

7.5 Saline and Sodic Soils

Accumulation of salts can result in three soil conditions: saline, saline-sodic and sodic soils. Each of these soil conditions has distinct characteristics that can be observed in the field, which are useful for diagnosing the problem. Completely white soils are saline, soils with a brownish-black crust are sodic, and grey-coloured soils are generally saline-sodic. The following physical observations/symptoms may be helpful in diagnosing salt-related soil problems:

**Saline Soils**

By definition, a saline soil is a non-sodic soil containing sufficient soluble salt to adversely affect the growth of most crop plants with a lower limit of electrical conductivity of the saturated extract (ECe) being 4 deciSiemens / meter (dS/m), which is equivalent to a value of 4 mmhos/cm. Soil salinity is caused by several factors. Soils may become saline as a result of land use,
including the use of irrigation water with high levels of salt. Seawater is also a source of salts in low-lying areas along the coast through tidal estuaries or when rainfall in coastal regions mixes with sea spray. Saltwater intrusion into freshwater aquifers may occur when wells are close to the coast and water is pumped to the surface for various purposes, including irrigation. Irrigating from salt-impacted wells or saline industrial water may lead to the formation of saline soils.

Soil Salinity Measurements
Problems due to soil salinity and sodicity in soil are commonly evaluated by laboratory testing. The following laboratory measurements are typically used to determine the extent of these problems:

1. **Electrical Conductivity (EC)** – Measures the ability of the soil solution to conduct electricity and is expressed in decisiemens per meter (dS/m, which is equivalent to mmhos/cm). Because pure water is a poor conductor of electricity, increases in soluble salts result in proportional increases in the solution EC. The standard procedure for salinity testing is to measure EC of a solution extracted from a soil wetted to a “saturation paste.” According to U.S. Salinity Laboratory Staff (1954), a saline soil has an EC of the saturated paste extract of more than 4 dS/m, a value that corresponds to approximately 40 mmol salts per liter. Crops vary in their tolerance to salinity and some may be adversely affected at ECs less than 4 dS/m. Salt tolerances are known for common crops. For example, peach is sensitive, whereas cotton is more salt tolerant (Maas, 1990). Beets and asparagus are very tolerant of salinity.

2. **Total Soluble Salts (TSS)** – Refers to the total amount of soluble salts in a soil-saturated paste extract expressed in parts per million or milligrams per liter (ppm or mg/L). A linear relationship exists between TSS and EC within a certain range that can be useful to closely estimate soluble salts in a soil solution or extract. The ratio of TSS to EC of various salt solutions ranges from 550 to 700 ppm per dS/m. Sodium chloride, the most common salt, has a TSS of 640 ppm per dS/m. So if EC is known, TSS can be estimated using the formula below:

3. **Sodium Adsorption Ratio (SAR)** – A widely accepted index for characterizing soil sodicity, which describes the proportion of sodium to calcium and magnesium in soil solution. The formula to calculate SAR is given below, with concentrations expressed in milliequivalents per liter (meq/L) analyzed from a saturated paste soil extract.

\[
SAR = \frac{[Na^+]^{1/2}}{[Ca^{2+}] + [Mg^{2+}]}^{1/2}
\]

When SAR is greater than 13, the soil is called a sodic soil. Excess sodium in sodic soils causes soil particles to repel each other, preventing the formation of soil aggregates. This results in a very tight soil structure with poor water infiltration, poor aeration and surface crusting, which makes tillage difficult and restricts seedling emergence and root growth (Munshower, 1994; Seelig, 2000; Horneck et al., 2007).

4. **Exchangeable Sodium Percentage (ESP)** – Another index that characterizes soil sodicity. As noted above, excess sodium causes poor water movement and poor aeration. By definition, sodic soil has an ESP greater than 15 (US Salinity Lab Staff, 1954). ESP is the sodium adsorbed on soil particles as a percentage of the Cation Exchange Capacity (CEC). It is calculated as:

\[
ESP = \frac{[Na^+]}{CEC} \times 100
\]

CEC is often estimated as the sum of the major exchangeable cations, including hydrogen. Both cations and CEC are expressed as meq/100g. ESP can also be calculated as:
\[
ESP = \frac{[Na^+]}{[Ca^{2+} + Mg^{2+} + Na^+ + K^+]} \times 100
\]

ESP is used to characterize the sodicity of soils only, whereas SAR is applicable to both soil and soil solution or irrigation water. The Natural Resources Conservation Service (NRCS) provides the following classification of salt-affected soils using the saturated paste extraction:

<table>
<thead>
<tr>
<th>Class</th>
<th>EC (mmhos/cm)</th>
<th>SAR</th>
<th>ESP</th>
<th>Typical soil</th>
<th>Structural condition*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>Below 4.0</td>
<td>Below 13</td>
<td>Below 15</td>
<td>Flocculated</td>
<td></td>
</tr>
<tr>
<td>Saline</td>
<td>Above 4.0</td>
<td>Below 13</td>
<td>Below 15</td>
<td>Flocculated</td>
<td></td>
</tr>
<tr>
<td>Sodic</td>
<td>Below 4.0</td>
<td>Above 13</td>
<td>Above 15</td>
<td>Dispersed</td>
<td></td>
</tr>
<tr>
<td>Saline-Sodic</td>
<td>Above 4.0</td>
<td>Above 13</td>
<td>Above 15</td>
<td>Flocculated</td>
<td></td>
</tr>
</tbody>
</table>

*Soil structural condition also depends on other factors not included in the NRCS classification system, including soil organic matter, soil texture and EC of irrigation water (Horneck et al., 2007).

**Sodic Soils**

Sodic soils are characterized by a disproportionately high concentration of sodium (Na) in their cation exchange complex. They are usually defined as containing an exchangeable sodium percentage greater than 15%. These soils tend to occur within arid to semiarid regions and are innately unstable, exhibiting poor physical and chemical properties, which impede water infiltration, water availability, and ultimately plant growth.

**Saline-Sodic Soils**

Saline-sodic soils have an EC greater than 4 dS/m and a Sodium Adsorption Ratio (SAR) greater than 13 in their saturation extract.

**Management**

In managing saline and sodic soils, care must be used to prevent further degradation. To prevent further degradation: 1) plant appropriate plants, particularly late maturing, deep rooted plants with high salt tolerance; 2) collect soil and water samples to identify the scope and magnitude of the problem; 3) eliminate source of salt or balance salt additions with salt loses; 4) apply chemicals such as gypsum to sodic soils if needed; 5) apply crop residues to improve water infiltration, and 6) apply irrigation water to leach salts from the soil.

In many areas, salts typically concentrate near the soil surface in areas with high water tables. In these areas, water and salts dissolved in the water rise through capillary movement from the water table to the surface. Water that evaporates at the soil surface is replaced by more water from the water table. The nest result is accumulation of salts. Capillary action provides a continuous transport of salts to the soil surface.

For sodic soils, high Sodium (Na) can greatly reduce water infiltration. If a problem with Na is suspected, a soil sample should be collected and a water extract from that soil analyzed for Na, Ca, and Mg. Based on this value, the Sodium adsorption ratio (SAR) should be calculated. If Na is a problem, then the long term goal should be to prevent further degradation and reduce new Na additions. This can be accomplished providing drainage, adding low Na manure or gypsum, or lowering the pH (if the soil pH is high) with elemental sulphur (S). If gypsum is present at deeper soil depths, tillage may help. If drainage and salt amendments are not possible, consider placing the field into pasture and planting it with grasses tolerant to salt and Na.
**8.0 INFRARED SPECTROSCOPY**

**Infrared spectroscopy (IR spectroscopy or Vibrational Spectroscopy)** is the spectroscopy that deals with the infrared region of the electromagnetic spectrum, that is light with a longer wavelength and lower frequency than visible light. It covers a range of techniques, mostly based on absorption spectroscopy. As with all spectroscopic techniques, it can be used to identify and study chemicals. For a given sample which may be solid, liquid, or gaseous, the method or technique of infrared spectroscopy uses an instrument called an infrared spectrometer (or spectrophotometer) to produce an infrared spectrum. A basic IR spectrum is essentially a graph of infrared light absorbance (or transmittance) on the vertical axis vs. frequency or wavelength on the horizontal axis. Typical units of frequency used in IR spectra are reciprocal centimeters (sometimes called wave numbers), with the symbol cm$^{-1}$. Units of IR wavelength are commonly given in micrometers (formerly called “microns”), symbol μm, which are related to wave numbers in a reciprocal way. A common laboratory instrument that uses this technique is a Fourier transform infrared (FTIR) spectrometer. Two-dimensional IR is also possible as discussed below.

The infrared portion of the electromagnetic spectrum is usually divided into three regions; the near-, mid- and far-infrared, named for their relation to the visible spectrum. The higher-energy near-IR, approximately 14000 - 4000 cm$^{-1}$ (0.8–2.5 μm wavelength) can excite overtone or harmonic vibrations. The mid-infrared, approximately 4000 - 400 cm$^{-1}$ (2.5–25 μm) may be used to study the fundamental vibrations and associated rotational-vibrational structure. The far-infrared, approximately 400 - 10 cm$^{-1}$ (25-1000 μm), lying adjacent to the microwave region, has low energy and may be used for rotational spectroscopy. The names and classifications of these sub-regions are conventions, and are only loosely based on the relative molecular or electromagnetic properties.

**8.1 Practical use of IR spectroscopy**

The infrared spectrum of a sample is recorded by passing a beam of infrared light through the sample. When the frequency of the IR is the same as the vibrational frequency of a bond or collection of bonds, absorption occurs. Examination of the transmitted light reveals how much energy was absorbed at each frequency (or wavelength). This measurement can be achieved by scanning the wavelength range using a monochromator. Alternatively, the entire wavelength range is measured using a Fourier transform instrument and then a transmittance or absorbance spectrum is generated using a dedicated procedure.

This technique is commonly used for analyzing samples with covalent bonds. Simple spectra are obtained from samples with few IR active bonds and high levels of purity. More complex molecular structures lead to more absorption bands and more complex spectra.

Infrared spectroscopic techniques are highly sensitive to both organic and inorganic phases of the soil, making their use in the agricultural and environmental sciences particularly relevant. Intense fundamental molecular frequencies related to soil components occur in the MIR between wavelengths 2500 and 25,000 nm. Weak overtones and combinations of these fundamental vibrations due to the stretching and bending of NH, OH and CH groups dominate the NIR (700 -2500 nm) and electronic transitions the VIS (400 -700 nm) portions of the electromagnetic (EM) spectrum. Quantitative spectral analysis of soil using visible and infrared reflectance spectroscopy requires sophisticated statistical techniques to discern the response of soil attributes from spectral characteristics.

Principal components regression (PCR) and partial least squares regression (PLSR) (e.g. are the most common techniques for spectral calibration and prediction. PLSR is performed in a slightly different manner to PCR. Rather than first decomposing the spectra into a set of eigenvectors and scores and performing the regression with soil attributes in a separate step, PLSR actually uses the soil information during the decomposition process. PLSR takes advantage of the correlation that exists between the spectra and the soil, thus the resulting spectral vectors are directly related to the soil attribute. The advantages of PLSR are that it handles multicollinearity, it is robust in terms of data noise and missing
values, and unlike PCR it balances the two objectives
of explaining response and predictor variation (thus
calibrations and predictions are more robust) and it
performs the decomposition and regression in a single
step. (Geladi and Kowalski, 1986; Chang et al., 2001;
McCarty et al., 2002)

**Visible Near Infra-Red Spectroscopy**

Rapid technique to evaluate certain soil properties.
Amount of interaction with a specific component is
proportional to quantity of the component. VIS-NIRS has
been used in agriculture for assessing grain, fertilizers
and soil qualities (Ben-Dor and Banin, 1995; Faraji
et al., 2004; Mohan et al., 2005) and has proven to
be a rapid, convenient means of analyzing many soil
constituents at the same time. Soil properties that have
been calibrated with VIS-NIRS include the determination
of soil moisture, SOC content, electrical conductivity
(EC), cation exchange capacity (CEC), soil acidity, some
macro- and microelements (Dunn et al., 2002; Velasquez
et al., 2005). Absorption in the near-infrared spectral
region (780 - 2500 nm) is dominated by molecules that
contain strong bonds between light atoms. Specifically,
these are molecules that contain C-H, N-H or O-H bonds.
This makes the near infrared region particularly useful
for measuring forms of carbon, nitrogen and water. VIS-
NIRS is a rapid and non-destructive analytical technique
that correlates diffusely reflected near-infrared radiation
with the chemical and physical properties of materials
(Chang and Laird, 2002). One interesting advantage of
VIS-NIRS is that the size of spectrometers is rather small
so that they can be field-portable (Christy, 2008).

To generate a soil spectrum, radiation containing all
relevant frequencies in the particular range is directed to
the sample. Depending on the constituents present in the
soil the radiation will cause individual molecular bonds
to vibrate, either by bending or stretching, and they will
absorb light, to various degrees, with a specific energy
quantum corresponding to the difference between two
energy levels. As the energy quantum is directly related
to frequency (and inversely related to wavelength), the
resulting absorption spectrum produces a characteristic
shape that can be used for analytical purposes (Miller,
2001). The frequencies at which light is absorbed
appear as a reduced signal of reflected radiation and
are displayed in % reflectance (R), which can then
be transformed to apparent absorbance: $A = \log(1/R)$
(Fig.8.1.2).

The Soil Properties Predicted with VNIR include the
following

- Sand, silt, clay
- Organic C, organic matter, total C
- C:N ratio
- Biomass
- Exchangeable calcium (Ca), magnesium (Mg),
  potassium (K)
- Iron (Fe)
- Phosphorus (P)
- pH
- Water content
- Electrical conductivity

Showing approximately where the combination, first,
second, and third overtone (OT) vibrations occur, as well
as the visible (vis) range.

Field use of vis-NIR
Systems developed for field measurements with modern scanning instruments apparently do not suffer significantly from moving samples. These systems include soil penetrating shanks equipped with a fiber optic probe protected by a sapphire glass at the bottom (Christy, 2008; Shibusawa et al., 2001; Stenberg et al., 2007), or without (Mouazen et al., 2005a). The bottom of the probe should be in close contact to the soil at all times. Automatic systems for identifying and filtering noisy and contaminated spectra are nevertheless required. Lost probe-soil contact due to vibration and shakiness of draught vehicle result to noisy spectra (Stenberg et al., 2007). In addition, topographical variation and slope changes across the field are contributing factors. This system uses a slow speed tractor fitted with soil scanning devices and a computer where the signals are transmitted and interpreted.

Soil quality and fertility assessment
A number of studies have shown the potential for vis–NIR to be used directly for the characterisation of soil quality, or soil fertility. The rationale for this is that the spectra contain information on soil organic and mineral composition – the fundamental building blocks of soil. Therefore the spectra should be useful for characterizing changes in quality and or fertility.

Benefits of vis-NIR for Soil Analysis
• Low cost per-sample
• High throughput: hundreds, even thousands off samples per day with automation
• Little or no sample preparation
• Possible to perform the analysis in the field
• Single spectrum to predict quantity off multiple soil properties

Fourier Transform Infrared (FTIR) spectroscopy
Fourier transform infrared spectroscopy is a measurement technique that allows one to record infrared spectra. Infrared light is guided through an interferometer and then through the sample (or vice versa). A moving mirror inside the apparatus alters the distribution of infrared light that passes through the interferometer. The signal directly recorded, called an “interferogram”, represents light output as a function of mirror position. A data-processing technique called Fourier transform turns this raw data into the desired result (the sample’s spectrum): Light output as a function of infrared wavelength (or equivalently, wave number). A sample’s spectrum is always compared to a reference.

An alternate method for acquiring spectra is the “dispersive” or “scanning monochromator” method. In this approach, the sample is irradiated sequentially with various single wavelengths. The dispersive method is more common in UV-Vis spectroscopy, but is less practical in the infrared than the FTIR method.
One reason that FTIR is favored is called “Fellgett’s advantage” or the “multiplex advantage”: The information at all frequencies is collected simultaneously, improving both speed and signal-to-noise ratio. Another is called “Jacquinot’s Throughput Advantage”: A dispersive measurement requires detecting much lower light levels than an FTIR measurement. There are other advantages, as well as some disadvantages,[3] but virtually all modern infrared spectrometers are FTIR instruments.

Application of isotopes in soil fertility and plant nutrition studies

Isotopes are crucial for tracing nutrients dynamics and transformation within the soil-plant system. In general two types of isotopes have been used in agricultural studies. These include the stable and unstable isotopes.

For carbon, natural abundance method can be used to trace the C3/C4 plant signatures left upon land use transformation. This is crucial not only in agricultural studies but also in climatic studies in determination of carbon losses to atmosphere after residue decomposition. Radio-isotopes represent a quick way for tracing nutrient inputs into the soil and release to the atmosphere. Radio-active isotopes (radiotracers) are important in soil fertility management for quantification of biological nitrogen fixation, availability of nutrients in the soil, fertilizer use efficiency, residual effect of applied amendments, salinity of soil and water, relative efficiency of applied organic manures, evapo-transpiration and photosynthesis amongst others.

Relative contribution of different sources of soil organic matter is obtained by labelling organic residue with $^{15}$N or $^{14}$C measuring $^{14}$C by liquid scintillation technique and $^{15}$N by mass spectrometry. Determination of turnover time for different fractions on a molecular level, $^{13}$C/$^{12}$C ratio which is expressed as delta (δ) value in soil system is used. δ$^{13}$C provides information about the stability of different soil organic fractions and the capacity of soil to act as a sink for global carbon levels on short and long term basis.

In this manual, isotope methods are presented as a brief overview. For detailed information the reader is referred to FAO/IAEA (2001) “Use of isotope and radiation methods in soil and water management and crop nutrition”. The most common methods used in analyzing carbon isotope content with particular emphasis on their analytical limits are presented in Table 8.1.1.

<table>
<thead>
<tr>
<th>Analytical method</th>
<th>Acronym</th>
<th>Measurement</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope ratio mass Spectrometry</td>
<td>IRMS</td>
<td>$^{13}$C/$^{12}$C ratios in bulk samples (1–2 mg C)</td>
<td>Well established, cheap</td>
<td>Large sample size required</td>
</tr>
<tr>
<td>Gas chromatography combustion-IRMS</td>
<td>GC-c-IRMS</td>
<td>$^{13}$C/$^{12}$C ratios in specific compounds (after their separation by GC)</td>
<td>High precision in analysis of specific compounds</td>
<td>Sample preparation is tedious</td>
</tr>
<tr>
<td>Laser ablation-IRMS</td>
<td>LA-IRMS</td>
<td>$^{13}$C/$^{12}$C ratios of structures in situ (after targeted combustion by laser)</td>
<td>Appropriate for in-situ analysis (e.g. soil structures)</td>
<td>Sample preparation is tedious</td>
</tr>
<tr>
<td>Accelerator mass Spectrometry</td>
<td>AMS</td>
<td>$^{14}$C/$^{12}$C ratios in small samples (&lt;100 mg C)</td>
<td>Very high resolution and analytical precision</td>
<td>Expensive</td>
</tr>
<tr>
<td>Stable isotope probing</td>
<td>SIP</td>
<td>Separates $^{13}$C-labeled DNA (or RNA) from unlabeled DNA</td>
<td>Identification of active microorganisms</td>
<td>Further refinements needed</td>
</tr>
<tr>
<td>Isotope Scintillation</td>
<td>IS</td>
<td>Detection of $^{14}$C signal</td>
<td>Easy sample preparation, analysis and high level precision</td>
<td>$^{14}$C is a radioactive material</td>
</tr>
</tbody>
</table>
Isotopic techniques in N Fertilizer Use Efficiency

In isotopic-aided fertilizer experiments, a labeled fertilizer is added to the soil and the amount of fertilizer nutrient that a plant has taken up is tracked through the plant system. A summary of isotope techniques for analysis and tracking of the fate of various soil nutrients is presented in table 8.1.2. By use of this method, different fertilizer practices (placement, timing, sources, etc.) can be studied in details. The first parameter to be determined when studying the fertilizer uptake by a crop by means of the isotope techniques is the fraction of the nutrient in the plant derived from the (labeled) fertilizer, i.e.: \( f_{diff} \).

Often this fraction is expressed as a percentage, i.e.:

\[
\text{% diff} = f_{diff} \times 100
\]  
(Equation 1)

The actual procedure followed in the calculation of this fraction and other derived parameters for nitrogen using 15N labeled materials is given below:

Measurements required for \(^{15}\text{N} \) experiments

In summary, for all field and greenhouse experiments with 15N (or any other stable isotope) labeled materials, the following basic primary data need to be recorded for each plot:

1. Dry matter (D.M.) yield for the whole plant or subdivided into plant parts.
2. Total N concentration (% N in dry matter) of the whole plant or plant parts as in point 1. This is done by chemical methods, e.g. Kjeldahl or by combustion (Dumas).
3. Plant % 15N abundance, which is analyzed by emission or mass spectrometry.
4. Fertilizer % 15N abundance.
5. 15N labeled fertilizer(s) used and N rate(s) of application.

Calculations for experiments with \(^{15}\text{N} \)

The calculations of the amount of N fixed using the \(^{15}\text{N} \) natural abundance method are based on the fact that with increasing N fixation the abundance of \(^{14}\text{N} \) in the N-fixing plant declines as nitrogen assimilated from the soil is “diluted” by atmospheric \( \text{N}_2 \) of lower \(^{15}\text{N} \) abundance fixed in its root nodules.

\%
\(^{15}\text{N} \) abundance is transformed into atom % \(^{15}\text{N} \) excess by subtracting the natural abundance (0.3663 atom %N) from the % N abundance of the sample. Afterwards the following calculations can be made:

\[
\text{atom %}^{15}\text{N excess}_{\text{plant}} = \text{atom %}^{15}\text{N excess}_{\text{fertilizer}} \times 100
\]  
(Equation 2)

Dry matter yield per unit area:

\[
\text{DM yield (kg/ha)} = \text{FW(kg)} \times \frac{10000 \text{ (m}^2 \text{/ ha)}}{\text{area harvested (m}^2\text{)}} \times \frac{\text{SDW(kg)}}{\text{SFW(kg)}}
\]  
(Equation 3)

Where FW is fresh weight per area harvested and SDW and SFW are subsample dry and fresh weight, respectively.

\[
\text{N yield (kg/ha)} = \text{DM yield (kg/ha}) \times \frac{\text{%N}}{100}
\]  
(Equation 4)

\[
\text{Fertilizer N yield (kg/ha)} = \text{N yield (kg/ha}) \times \frac{\text{%N}_{diff}}{100}
\]  
(Equation 5)

\[
\% \text{ fertilizer N utilization} = \frac{\text{Fertilizer N yield}}{\text{Rate of N application}} \times 100
\]  
(Equation 6)

Isotopic Techniques in P Fertilizer Use Efficiency

Phosphorus has one stable isotope \(^{31}\text{P} \) and several radioisotopes (from \(^{26}\text{P} \) to \(^{30}\text{P} \) and from \(^{32}\text{P} \) to \(^{38}\text{P} \)), but only two of them \((^{32}\text{P} \) and \(^{33}\text{P} \)) are suitable for agronomic studies. The main characteristics of these radioactive P isotopes are shown in Table 8.1.3.

Calculations for experiments with \(^{32}\text{P} \) and/or \(^{33}\text{P} \)

The following calculations need to be made:

1. The S.A. of plant and fertiliser
2. \( \% \text{P}_{diff} = (\text{S.A. plant} / \text{S.A. fertiliser}) \times 100 \)
3. Dry matter yield per unit area:
   \[ \text{DM yield (kg/ha)} = \text{FW(kg)} \times (10 \ 000 \text{ (m}^2 \text{/ ha)}) \times \frac{\text{SDW(kg)}}{\text{SFW(kg)}} \]
4. \( \text{P yield (kg/ha)} = \text{DM yield (kg/ha}) \times \frac{\text{P}_{diff}}{100} \)
5. Fertiliser P yield (kg/ha) = P yield (kg/ha) x (% pdiff / 100)
6. % fertiliser P utilisation = (Fert. P yield / Rate of P application) x 100

Natural Abundance of C Isotopes

The ratio of \(^{13}\text{C} \) to \(^{12}\text{C} \) in the atmosphere can vary with different physiographic parameters such as altitude,
<table>
<thead>
<tr>
<th>Element</th>
<th>Most abundant isotope</th>
<th>Tracer isotope</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>$^{14}\text{N}$</td>
<td>$^{13}\text{N}$</td>
<td>Limited because of short half life. Very short term studies on N2 fixation, de-nitrification</td>
</tr>
<tr>
<td></td>
<td>$^{14}\text{N}$</td>
<td>$^{15}\text{N}$</td>
<td>N-14 enriched (N-15 depleted) materials for single season fertilizer use efficiency studies</td>
</tr>
<tr>
<td></td>
<td>$^{15}\text{N}$</td>
<td></td>
<td>Fertilizer N use efficiency, biological nitrogen fixation, N balance, N transformation in soils, N availability from organic-materials, animal nutrition studies</td>
</tr>
<tr>
<td></td>
<td>$^{33}\text{P}$</td>
<td></td>
<td>Root autoradiography, diffusion in soil, double labeling for root activity patterns, fertilizers P use efficiency</td>
</tr>
<tr>
<td>Sulfur</td>
<td>$^{32}\text{S}$</td>
<td>$^{34}\text{S}$</td>
<td>Potentially useful, environmental pollution, ecological and medical research</td>
</tr>
<tr>
<td></td>
<td>$^{35}\text{S}$</td>
<td></td>
<td>Uptake from atmosphere (SO$_2$), S cycling studies, availability from soil</td>
</tr>
<tr>
<td>Other elements</td>
<td>Carbon</td>
<td>$^{12}\text{C}$</td>
<td>$^{11}\text{C}$</td>
</tr>
<tr>
<td></td>
<td>$^{12}\text{C}$</td>
<td>$^{13}\text{C}$</td>
<td>C-12 enriched (C-13 depleted) Organic matter reaction mechanisms work</td>
</tr>
<tr>
<td></td>
<td>$^{13}\text{C}$</td>
<td>$^{14}\text{C}$</td>
<td>Soil organic matter studies in ecosystems, photosynthesis, C translocation, C cycling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{12}\text{C}$</td>
<td>Photosynthesis and C translocation, Soil organic matter studies, C balance studies</td>
</tr>
</tbody>
</table>

Table 8.1.3. Summary of main characteristics of P isotopes used in plant nutrition

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Half-life</th>
<th>Radiation characteristics</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{32}\text{P}$</td>
<td>14.3 days</td>
<td>$\beta^-$, 1.71 MeV(E_max)</td>
<td>Exchangeable P in soils, P availability from P fertilisers, Plant root distribution / activity, Residual P fertilizer availability</td>
</tr>
<tr>
<td>$^{33}\text{P}$</td>
<td>24.4 days</td>
<td>$\beta^-$, 0.248 MeV(E_max)</td>
<td>Auto-radiography, Diffusion in soils, Double labeling with $^{32}\text{P}$</td>
</tr>
</tbody>
</table>

Latitude and temperature as well as by some biological processes (Lefroy et al., 1995). When plants fix carbon during photosynthesis there is a degree of discrimination between the amount of $^{13}\text{C}$ and $^{12}\text{C}$. Discrimination occurs during the carboxylation step in photosynthesis, with greater discrimination against $^{13}\text{C}$ in C3 (Calvin cycle) plants than in C4 (Hatch-Slack cycle) plants, due to the greater discrimination in the primary carboxylation step of C3 plants. This primary carboxylation step is catalyzed by the enzyme ribulose biphosphate carboxylase (RuBP).
resulting in a lower $^{13}$C/$^{12}$C ratio in C3 plants than in C4. CAM plants (crassulacean acid metabolism) plants show variable discrimination, but it is more often similar to C4 plants.

The $^{13}$C/$^{12}$C ratio is generally measured as $\delta^{13}$C. A C4 species such as maize will have a $\delta$ 13C value of approximately -12‰ whereas in a C3 species such as wheat or rice it will be approximately -26‰. The $\delta^{13}$C of SOM is comparable to that of the source plant material (Schwartz et al., 1986) and thus every change in vegetation between C3 and C4 plants results in a corresponding change in the $\delta^{13}$C value of the SOM (Lefroy et al., 1995). This means that when C3 plants are grown in soils, which had previously been under C4 vegetation (or vice versa) there is virtually an in situ labeling of the organic matter incorporated into the soil. Cerrie et al. (1985) first used this method in order to measure the turnover rate of organic matter in a 50-year-old sugarcane field, after forest clearing. Schwartz et al. (1986) used this principle to investigate changes in vegetation in the Congo while Skjemstad et al. (1990) studied the turnover of organic matter in pastures using this method. This principle has also been used by Balesdent et al. (1987) and Lefroy et al. (1993) to investigate changes in SOM as a result of cropping, while Bonde et al. (1992) used it to quantify maize root derived soil C.

Measurement of $^{13}$C

$^{13}$C is most often determined in CO2 produced from a solid sample combusted in a stream of oxygen. The two pieces of equipment most commonly used are Leco and Carlo-Erba furnaces linked to a mass spectrometer set to measure the mass 45/44 ratio. The results are expressed as $\delta^{13}$C (‰), which is not the absolute isotope ratio but that relative to a standard. The original standard used was a limestone fossil of Belemnitella americana (PDB) from the Cretaceous Pee Dee formation in South Carolina, USA. Since this material is no longer available other standards which have been cross calibrated are used.

Calculation of Proportion of Added Residues Remaining in the Soil

The proportion of soil C derived from the C3 (or C4) plant can be calculated from (Equation 13)

$$\chi = \frac{(\delta f - \delta s)}{(\delta r - \delta s)}$$

(Equation 13)

Where $\delta f$ is the $\delta^{13}$C value of the soil at time t after the addition of the residues, $\delta s$ is the $\delta^{13}$C of the original soil or soil of the control treatment and, $\delta r$ is the $\delta^{13}$C of the C3 (or C4) plant residue added to the soil.

The stable isotope ratio was calculated from the measured C isotope ratios of the sample and a standard calibrated against the Pee Dee Belemnite (PDB) standard gases as

$$\delta^{13}\text{C (‰) = } \left( \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{sample}}} \right) 1000$$

where $\delta^{13}$C is the parts per thousand, or per mil (‰), of the sample relative to that of the PDB standard, and R is the mass 45/44 (i.e., $^{13}$C/$^{12}$C) ratio of the sample or standard CO$_2$ gas.

If the total C content C of the soil is known then the absolute quantity X of carbon from the C3 (or C4) plants can be determined from (Equation 14).

$$X = \chi \times C$$

(Equation 14)

The absolute quantity Y of residual carbon from the initial soil can be determined from (Equation 15).

$$Y = C(1 - x)$$

(Equation 15)

8.2 Estimation of maize-derived (C$_4$) Carbon

In scenarios where land use changes from C3 to C4 such as conversion of land that is naturally under C3 plant species to C4 plant species (conversion from forest to agricultural use under maize) the contribution of C4 to the soil carbon content can be calculated as follows:

The proportion of C originating from corn (C$_4 f$) is calculated using a two end-member mixing model:

$$\delta^{13}\text{C}_{\text{SOM}} = f_{C4} \delta^{13}\text{C}_{\text{com}} + (1-f_{C4}) \delta^{13}\text{C}_{C3}$$
Therefore the added maize residue contributed 27% of the soil C after 60 days.

The total content of residue C remaining is
\[ X = \chi \times C \]
\[ = 0.27 \times 13830 \text{ (i.e. } 13.83 \text{ mg/g x 1000g)} \]
\[ = 3734 \text{ mg} \]

The total quantity of native soil C remaining is
\[ Y = C(1 - \chi) \]
\[ = 13830 \text{ (1 - 0.27)} \]
\[ = 10096 \text{ mg} \]

or

The total concentration of residue C in the soil is
\[ X = \chi \times C \]
\[ = 0.27 \times 13.83 \text{ mg/g} \]
\[ = 3.73 \text{ mg/g} \]

The total concentration of native soil C remaining is
\[ Y = C(1 - \chi) \]
\[ = 13.83 \text{ (1-0.27)} \text{ mg/g} \]
\[ = 10.10 \text{ mg/g} \]

Example calculation
In an incubation experiment 7.50 g of maize leaf with -11.5 ‰ δ^{13}C was mixed into 1000g of soil, which had a total C concentration of 10.00 mg/g and -23.5‰ δ^{13}C and incubated for 60 days at 75% of field capacity. At the end of the experiment the total C concentration was 13.80 mg/g and the δ^{13}C value was δ 20.26 ‰ δ^{13}C. What proportion of soil C was made up of the added maize leaf?

\[
\chi = \frac{-20.26 - (-23.5)}{-11.5 - (-23.5)}
\]
\[
= \frac{-20.26 + 23.5}{-11.5 + 23.5}
\]
\[
= \frac{3.24}{12.00}
\]
\[
= 0.27
\]
Soil biology is the study of microbial and faunal activity and ecology in soil. Soil life (soil biota, soil fauna) or edaphon is a collective term that encompasses all the organisms that spend a significant portion of their life cycle within a soil profile, or at the soil-litter interface. These organisms include earthworms, nematodes, protozoa, fungi, bacteria and different arthropods. Soil biology plays a vital role in determining many soil characteristics. The decomposition of organic matter by soil organisms has an immense influence on soil fertility, plant growth, soil structure, and carbon storage.

The interconnectedness and complexity of this soil ‘food web’ means any appraisal of soil function must necessarily take into account interactions with the living communities that exist within the soil. The nutrients stored in the bodies of soil organisms prevent nutrient loss by leaching. Microbial exudates act to maintain soil structure, and earthworms are important in soil pore infrastructure that is crucial for root growth and soil gaseous exchange.

In a balanced soil, plants grow in an active and steady environment. Without the activities of soil organisms, organic materials would accumulate and litter the soil surface, and there would be no food for plants. The soil biota includes:

- **Mega-fauna**: size range - 20 mm upward, e.g. moles, rabbits, and rodents.
- **Macro-fauna**: size range - 2 to 20 mm, e.g. woodlice, earthworms, beetles, centipedes, slugs, snails, ants, and harvestmen.
- **Meso-fauna**: size range - 100 micrometers to 2 mm, e.g. tardigrades, mites and springtails.
- **Micro-fauna and Micro-flora**: size range - 1 to 100 micrometers, e.g. yeasts, bacteria, fungi, protozoa, roundworms, and rotifers.

Of these, bacteria and fungi play key roles in maintaining a healthy soil. They act as decomposers that breakdown organic materials to produce detritus and other breakdown products. Soil detritivores, like earthworms, ingest detritus and decompose it. Saprotrophs, well represented by fungi and bacteria, extract soluble nutrients from detritus. The ants (macro-faunas) help by breaking down the same way but they also provide the motion part as they move in their armies.

**Relationship between soil microorganisms (Micro-fauna and Micro-flora) and plants**

The mineral content of the soil and its structure are important for plants well-being, but it is the life in the earth that powers its cycles and provides its fertility. The soil microorganisms includes: bacteria, fungi, actinomycetes and yeast.

**Bacteria**

Most soil bacteria live close to plant roots and are often referred to as rhizobacteria. Bacteria live in soil water, including the film of moisture surrounding soil particles, and some are able to swim by means of flagella. The majority of the beneficial soil-dwelling bacteria need oxygen (and are thus termed aerobic bacteria), whilst those that do not require air are referred to as anaerobic, and tend to cause breakdown of dead organic matter. Aerobic bacteria are most active in a soil that is moist (but not saturated, as this will deprive aerobic bacteria of the air that they require), and neutral soil pH, and where there is plenty of food (carbohydrates and micronutrients from organic matter) available. The important roles that bacteria play are:

**Nitrification**

Nitrification is a vital part of the nitrogen cycle, wherein certain bacteria (which manufacture their own carbohydrate supply without using the process of photosynthesis) are able to transform nitrogen in the form of ammonium, which is produced by the decomposition of proteins, into nitrates, which are available to growing plants, and once again converted to proteins.

**Nitrogen fixation**

Nitrogen fixation is a process in which nitrogen (N₂) in the atmosphere is converted into ammonia (NH₃). Atmospheric nitrogen or molecular di-nitrogen (N₂) is relatively inert: it does not easily react with other chemicals to form new compounds. The fixation process frees nitrogen atoms from their triply bonded diatomic
form, N≡N, to be used in other ways. All biological nitrogen fixation is done by way of nitrogenase metallo-enzymes which contain iron, molybdenum, or vanadium. Microorganisms that can fix nitrogen are prokaryotes (both bacteria and archaea, distributed throughout their respective kingdoms) called diazotrophs.

Biological nitrogen fixation

Biological nitrogen fixation (BNF) occurs when atmospheric nitrogen is converted to ammonia by an enzyme called a nitrogenase. Nitrogenase is made up of two soluble proteins: component I and II. Component I known as MoFe protein or nitrogenase contains 2 Mo atoms, 28 to 34 Fe atoms, and 26 to 28 acid-labile sulfides, also known as a iron-molybdenum cofactor (FeMoco). Component I is composed of two copies each of two subunits (α and β); each subunit’s stability depends on the other in vivo. Component II known as Fe protein or nitrogenase reductase is composed of two copies of a single subunit. This protein has four non-heme Fe atoms and four acid-labile sulfides (4Fe-4S). Substrate binding and reduction takes place on component I, which binds to ATP and ferredoxin or flavodoxin proteins (Fdx orFld). Nitrogenase bonds each atom of nitrogen to three hydrogen atoms to form ammonia (NH₃). The nitrogenase reaction additionally produces molecular hydrogen as a side product, which is of special interest for people trying to produce H₂ as an alternative energy source to fossil fuels. The overall reaction for BNF is:

$$\text{N}_2 + 8 \text{H}^+ + 8 e^- \rightarrow 2 \text{NH}_3 + \text{H}_2$$

The process is coupled to the hydrolysis of 16 equivalents of ATP and is accompanied by the co-formation of one molecule of H₂O. The conversion of N₂ into ammonia occurs at a cluster called FeMoco, an abbreviation for the iron-molybdenum cofactor.

Nitrogen fixation occurs in the root nodules that contain bacteria (Bradyrhizobium for soybean, Rhizobium for most other legumes). Almost all legumes can fix nitrogen. The legume family (Leguminosae or Fabaceae) includes many important crop species such as pigeon pea, alfalfa, clover, common bean, peanut, cowpeas, lupines, soybean, and vetches and lentil.

Factors limiting biological nitrogen fixation

Interactions between the microsymbiont and the plant are complicated by edaphic, climatic, and management factors. A legume-Rhizobium symbiosis might perform well in a loamy soil but not in a sandy soil, in the sub-humid region but not in the Sahel, or under tillage but not in no-till plots. The following factors affect either the micro-symbiont, the host-plant, or both.

Edaphic Factors

Edaphic factors relate to the soil. The six main edaphic factors limiting biological nitrogen fixation are:

- **Excessive moisture** and water logging prevent the development of root hair and sites of nodulation, and interfere with a normal diffusion of O₂ in the root system of plants.
- **Drought reduces** the number of rhizobia in soils, and inhibits nodulation and N₂ fixation. Prolonged drought will promote nodule decay. Mycorrhizal infection has been found to improve tolerance of plants to drought (e.g., Acacia auriculiformis inoculated with the ectomycorrhizal Baletus suillus).
- **Soil acidity** and related problems of Calcium deficiency and aluminum and manganese toxicity adversely affect nodulation, N₂ fixation and plant growth.
- **Phosphorus deficiency** reduces nodulation, N₂ fixation and plant growth. Identification of plant species adapted to low-P soils is a good strategy to overcome this soil constraint. Mycorrhizal fungi play a key role in increasing plant P uptake with beneficial effects on N₂ fixation.
- **Mineral N** inhibits the Rhizobium infection process and also inhibits N₂ fixation. The former problem probably results from impairment of the recognition mechanisms by nitrates, while the latter is probably due to diversion of photosynthates toward assimilation of nitrates. Application of large quantities of fertilizer N (200 kg fertilizer N/ha) inhibits N₂ fixation, but low doses (<30 kg N/ha) of fertilizer N can stimulate early growth of legumes and increase their overall N₂ fixation. The amount of this starter N must be defined in relation to available soil N.
- **Various microelements** (Cu, Mo, Co, B) are necessary for N₂ fixation. Some of these are components of nitrogenase for example Mo.

Climatic Factors

The two important climatic determinants affecting BNF are temperature and light.
• Extreme temperatures affect N\textsubscript{2} fixation adversely. This is easy to understand because N\textsubscript{2} fixation is an enzymatic process. However, there are differences between symbiotic systems in their ability to tolerate high (>35°C) and low (<25°C) temperatures.

• Availability of light regulates photosynthesis, upon which biological nitrogen fixation depends. This is demonstrated by diurnal variations in nitrogenase activity.

Biotic Factors
Among biotic factors, the absence of the required rhizobia species constitutes the major constraint in the nitrogen fixation process. The other limiting biotic factors could be:
• Excessive defoliation of host plant,
• Crop competition, and
• Insects and nematodes

Inoculation of Legumes
If specific and effective rhizobia are absent in a soil, or if they are present in low numbers, it is necessary to introduce the rhizobia in that soil to ensure sufficient nodulation and nitrogen fixation. This is called inoculation and it is responsible for N fixation in legumes.

Inoculant rhizobia usually persist in the soil for long periods, particularly when the host is cultivated frequently or is permanent. Persistence of a strain is desirable because it obviates the need for inoculation in subsequent years, assuming inoculant strains maintain their original effectiveness.

Inoculation with rhizobia is usually recommended for newly introduced legumes. Most positive responses to inoculation are confined to crops which have specific requirements for Rhizobium, (e.g., Leucaena leucocephala, soybean). Indigenous legumes seldom respond to inoculation with introduced rhizobia because they nodulate with resident strains, even if these native rhizobia are not the most effective ones.

To be able to form nodules and fix nitrogen, bean seeds need to be inoculated with rhizobia. Each legume crop needs a different type of rhizobium bacteria, so always check you have the right inoculant for beans. Directions for using inoculants can be found on the package.

How to inoculate common bean seeds
1. Measure 15 kg of legume seed; this will be approximately 15 liters. Place in any container that will accommodate the seeds.
2. Measure one soda bottle (300 ml) of clean lukewarm water.
3. Pour the water into a larger bottle (500 ml plastic bottle) so that it is easier to mix the sugar.
4. Add 2 tablespoons of sugar to the water.
5. Mix thoroughly to get an even solution of sugar. This solution is called the sticker.
6. Add the sticker to the seed.
7. Mix the seed with sticker solution until all the seeds are evenly coated with the sticker.
8. Add the Rhizobium inoculant onto the seeds and sticker. The inoculant is the 125 g black powder contained in the pack.
9. Mix the seeds and the inoculant thoroughly but gently until all seeds are uniformly covered with the inoculant.
10. Protect the inoculated seed from direct sunlight by covering the container with paper, cloth or gunny bag and keep under a shade until planted.

For smaller amounts of seed, use 4 teaspoons or soda bottle-tops (20 ml) of the sticker solution, and 2 heaped teaspoons or soda bottle-tops (10 g) of inoculant for every 1 kg of seed.

Facts about inoculants:
• The roots of legumes and Rhizobium bacteria work together to biologically fix nitrogen. Inoculants contain the bacteria that help the soybean to make nitrogen.
• Inoculants are much cheaper than nitrogen fertilizer. Each legume crop needs a different type of Rhizobium bacteria, so always check you have the right inoculant for the crop you want to sow
• Inoculants lose their effectiveness when stored in an open package. Therefore do not open the package until you are ready to use it.
• Inoculants also lose their effectiveness when exposed to heat or direct sunlight. Therefore always store the package in a cool place in the house.

Directions for using inoculants can be found on the package.

How to inoculate depends on the type of inoculant you
How to increase BNF and N₂ fixing ability
The nitrogen fixation process is influenced by factors such as:

- Presence and effectiveness of rhizobia, pest damage,
- Plant genotype and age,
- Plant and rhizobia interactions,
- Changes in soil physiochemical conditions, and
- Various management practices such as tree pruning or pesticide application that can affect both symbiotic partners.

Four common approaches to enhance biological nitrogen fixation are:

- Inoculation with proven strains (covered above),
- Microbial screening for improved strains,
- Host-plant screening and breeding, and
- Adoption of cropping systems and cultural practices.

Root nodule symbioses
A symbiotic relationship is one in which two organisms form a mutually beneficial relationship. These soil bacteria infect the roots of the plant and form structures known as nodules. A good example is the chemical reactions process known as BNF that take place in the nodules. Plants that contribute to nitrogen fixation include the legume family -Fabaceae - with taxa such as kudzu, clovers, soybeans, alfalfa, lupines, peanuts etc. They contain symbiotic bacteria called rhizobia within nodules in their root systems, producing nitrogen compounds that help the plant to grow and compete with other plants. When the plant dies, the fixed nitrogen is released, making it available to other plants; this helps to fertilize the soil (Postgate, 1998).

De-nitrification
While nitrogen fixation converts nitrogen from the atmosphere into organic compounds, a series of processes called de-nitrification returns an approximately equal amount of nitrogen to the atmosphere. Denitrifying bacteria tend to be anaerobes, or facultatively anaerobes (can alter between the oxygen dependent and oxygen independent types of metabolisms), including Achromobacter and Pseudomonas. The purification process caused by oxygen-free conditions converts nitrates and nitrites in soil into nitrogen gas or into gaseous compounds such as nitrous oxide or nitric oxide. In excess, de-nitrification can lead to overall losses of available soil nitrogen and subsequent loss of soil fertility. However, fixed nitrogen may circulate many times between organisms and the soil before de-nitrification returns it to the atmosphere.

Actinobacteria
Actinobacteria are critical in the decomposition of organic matter and in humus formation, and their presence is responsible for the sweet “earthy” aroma associated with a good healthy soil. They require plenty of air and a pH between 6.0 and 7.5, but are more tolerant of dry conditions than most other bacteria and fungi.

Fungi
Fungi have no chlorophyll, and are not able to photosynthesize. They cannot use atmospheric carbon dioxide as a source of carbon, therefore they are chemoheterotrophic, meaning that, like animals, they require a chemical source of energy rather than being able to use light as an energy source, as well as organic substrates to get carbon for growth and development.

Many fungi are parasitic, often causing disease to their living host plant, although some have beneficial relationships with living plants, as illustrated below. In terms of soil and humus creation, the most important fungi tend to be saprotrophic; that is, they live on dead or decaying organic matter, thus breaking it down and converting it to forms that are available to the higher plants. A succession of fungi species will colonize the dead matter, beginning with those that use sugars and starches, which are succeeded by those that are able to break down cellulose and lignin.

Fungi spread underground by sending long thin threads known as mycelium throughout the soil; these threads can be observed throughout many soils and compost heaps. From the mycelia the fungi is able to throw up its fruiting bodies, the visible part above the soil (e.g., mushrooms, toadstools, and puffballs), which may contain millions of spores. When the fruiting body bursts, these spores are dispersed through the air to settle in fresh environments, and are able to lie dormant for up to years until the right conditions for their activation arise or the right food is made available.
**Mycorrhizae**

Fungi that are able to live symbiotically with living plants, creating a relationship that is beneficial to both are known as Mycorrhizae (from *myco* meaning fungal and *rhiza* meaning root). Plant root hairs are invaded by the mycelia of the Mycorrhizae, which lives partly in the soil and partly in the root, and may either cover the length of the root hair as a sheath or be concentrated around its tip. The Mycorrhizae obtains the carbohydrates that it requires from the root, in return providing the plant with nutrients including nitrogen and moisture. Later the plant roots will also absorb the mycelium into its own tissues.

Beneficial Mycorrhizae associations are to be found in many of our edible and flowering crops that may include at least 80% of the *Brassica* and *Solanum* families (including tomatoes and potatoes), as well as the majority of tree species, especially in forest and woodlands. Here the Mycorrhizae create a fine underground mesh that extends greatly beyond the limits of the tree’s roots, greatly increasing their feeding range and actually causing neighbouring trees to become physically interconnected.

The benefits of mycorrhizal relations to their plant partners are not limited to nutrients, but can be essential for plant reproduction: In situations where little light is able to reach the forest floor, a young seedling cannot obtain sufficient light to photosynthesize for itself and will not grow properly in a sterile soil. But, if the ground is underlain by a Mycorrhizae mat, then the developing seedling will throw down roots that can link with the fungal threads and through them obtain the nutrients it needs, often indirectly obtained from its parents or neighbouring trees.

Recent research has shown that Arbuscular Mycorrhizae fungi produce glomalin, a protein that binds soil particles and stores both carbon and nitrogen. These glomalin-related soil proteins are an important part of soil organic matter.[3]

Not all plant/microbe interactions are invasions. The rhizosphere (the narrow region surrounding each root) is rich in biological activity as bacteria and other microbes feed on the carbon compounds exuded by roots. Plants may exude compounds that attract certain species to the rhizosphere that protect the roots from disease-causing species.

When microbes and plants compete for soil nutrients, microbes have an advantage because they are often suspended in the soil solution while plants must pull the soil solution towards their roots.

In an ideal situation, microbes will tie-up (immobilize) nitrogen and prevent its loss from the rooting zone when plants are not growing, and then will release (mineralize) nitrogen when crops are actively growing.

- **Decomposition**: turning organic compounds into other organic compounds
- **Mineralization**: turning organic matter into inorganic compounds that may be used by plants
- **Immobilization**: turning inorganic compounds into organic compounds. Farmers depend on bacteria for one more transformation:
- **Mineral transformation**: turning inorganic matter into other inorganic compounds. Bacteria that perform mineral transformations are important in nitrogen cycling. The roots of legumes host nitrogen-fixing bacteria that convert large amounts of dinitrogen (N₂) from the atmosphere into forms that plants can use. Some nitrogen-fixing bacteria live free in the soil.

**Benefits of the soil biological community**

- **Nutrient cycling**: When organisms consume food, they create more of their own biomass and they release wastes. The most important waste for crop growth is ammonium (NH₄⁺). Ammonium and other readily utilized nutrients are quickly taken up by other organisms, including plant roots. When a large variety of organisms are present, nutrients may cycle more rapidly and frequently among forms that plants can and cannot use.

- **Nutrient retention**: In addition to mineralizing or releasing nitrogen to plants, the soil food web can immobilize or retain nitrogen when plants are not rapidly growing. Nitrogen in the form of soil organic matter and organism biomass is less mobile and less likely to be lost from the rooting zone than inorganic nitrate (NO₃⁻) and ammonium (NH₄⁺).

- **Improved structure, infiltration, and water-holding capacity**: Many soil organisms are involved in the formation and stability of soil aggregates. Bacterial activity, organic matter, and the chemical properties of clay particles are responsible for creating micro-aggregates from individual soil particles. Earthworms and arthropods consume
small aggregates of mineral particles and organic matter, and generate larger fecal pellets coated with compounds from the gut. These fecal pellets become part of the soil structure. Fungal hyphae and root hairs bind together and help stabilize larger aggregates. Improved aggregate stability, along with the burrows of earthworms and arthropods, increases porosity, water infiltration, and water holding capacity.

- **Disease suppression**: A complex soil food web contains numerous organisms that can compete with disease-causing organisms. These competitors may prevent soil pathogens from establishing on plant surfaces, prevent pathogens from getting food, feed on pathogens, or generate metabolites that are toxic to or inhibit pathogens.

- **Degradation of pollutants**: An important role of soil is to purify water. A complex food web includes organisms that consume (degrade) a wide range of pollutants under a wide range of environmental conditions.

- **Biodiversity**: Greater food web complexity means greater biodiversity. Biodiversity is measured by the total number of species, as well as the relative abundance of these species, and the number of functional groups of organisms.

- **Reduced input costs**: Less fertilizer may be needed if nutrient cycling becomes more efficient and less fertilizer is lost from the rooting zone. Fewer pesticides are needed where a diverse set of pest-control organisms are active. As soil structure improves, tillage becomes easier and potentially less costly.

- **Pollution prevention**: Soil organisms filter and detoxify chemicals and absorb the excess nutrients that would otherwise become pollutants when they reach groundwater or surface water.

- **Improvement of yield and crop quality**: Soil organisms are key to forming good soil structure or tilth. Good tilth promotes better root development and water storage. Many microorganisms enhance crop growth or reduce the activity of disease organisms that can degrade the quality of food and feed.

**Estimation of nitrogen fixation**

From the biochemical reactions of BNF N₂ fixing systems contribute to the quality and quantity of agricultural production. Measurement of BNF can provide information on whether actual N₂ fixation in adequate. We discuss below two simple methods of BNF estimation. Measurement of BNF is a more reliable method than nodule counting, nodule weighing, or assessment of leghemoglobin.

**Short-term Estimation of BNF: Acetylene Reduction Assay**

Nitrogenase not only catalyzes the reduction of atmospheric N₂ to NH₃, but can also reduce acetylene (C₂H₂). The acetylene reduction assay (ARA) is carried out on detached nodules, detopped roots, or whole plants in a closed vessel containing 10% acetylene. A gas chromatograph is used to determine the amount of ethylene formed. Data are usually expressed as nanomoles or micromoles of ethylene produced per hour per plant or per weight unit of nodules. The acetylene reduction assay provides an instant measure of nitrogenase activity (but not necessarily of N₂ fixed) under the experimental conditions. For long-term estimates, a series of measurements must be performed to include diurnal, daily, and seasonal changes. Variation in light intensity, temperature, and moisture in the field will increase the level of variation of nitrogenase activity and will reduce the significance of integration of short-term assays. A problem that is inherent in ARA is the need to calibrate the rates of ethylene production with the actual rates of N₂ fixation. The commonly used ratio of 3:1 for acetylene reduced per N₂ fixed is not always valid. Also, nitrogenase activity of some legumes declines considerably once nodules or roots are detached from the rest of the plant. For plants with long roots, it is difficult to collect all the nodules. To minimize this limitation, the plants are confined to open ended chambers and ARA is done in situ.

**Medium-term Estimation of BNF: N-solute Analysis of Xylem Exudates**

N-solute analysis of xylem exudates is a medium-term type of estimate because it involves the integration of more than one hour of events. The underlying principle is based on the fact that nitrogen from BNF can be transported to the leaves in the form of (1) ureides, allantoin and allantoic acid, or (2) asparagine and glutamine. In agricultural soils, where nitrate is the most readily available form of N for plant growth, the solutes derived from soil mineral N will contain principally free nitrate and organic products of nitrate reduction in the roots. Correlations can be established between
the N\textsubscript{2} fixed nitrogen in forms (1), (2), and soil-derived N. Using these correlations, it should be possible to assess N\textsubscript{2} fixation, or at least to obtain an index of BNF by collecting and analyzing plant sap for the above-mentioned N compounds.

The methods are simple and have been used successfully in ureide legumes. Solute analysis can be used in farmers’ fields because it is virtually non-destructive. It is also relatively inexpensive. Repeated measurements are also required to fully integrate measurements of total N fixed over a long period of time.

9.1 Soil Organic Carbon (SOC)

Soil Organic Carbon (SOC) is the main source of energy for soil microorganisms. The ease and speed with which SOC becomes available is related to the SOM fraction in which it resides. In this respect, SOC can be partitioned into fractions based on the size and breakdown rates of the SOM in which it is contained (see table 10.1.1). The first three fractions listed are part of the active pool of SOM. Carbon sources in the active pool are relatively easy to break down.

Why it is important: SOC is one of the most important constituents of the soil due to its capacity to affect plant growth as both a source of energy and a trigger for nutrient availability through mineralization. SOC fractions in the active pool, previously described, are the main source of energy and nutrients for soil microorganisms. Humus participates in aggregate stability, and nutrient and water holding capacity.

Total Organic Carbon

Total organic carbon (TOC) is the carbon (C) stored in soil organic matter (SOM). Organic carbon (OC) enters the soil through the decomposition of plant and animal residues, root exudates, living and dead microorganisms, and soil biota. SOM is the organic fraction of soil exclusive of non-decomposed plant and animal residues. Nevertheless, most analytical methods do not distinguish between decomposed and non-decomposed residues. SOM is a heterogeneous, dynamic substance that varies in particle size, C content, decomposition rate, and turnover time.

SOM contains approximately 58% C; therefore, a factor of 1.72 can be used to convert OC to SOM. There is more inorganic C than TOC in calcareous soils. TOC is expressed as percent C per 100 g of soil. OC compounds, such as polysaccharides (sugars) bind mineral particles together into micro-aggregates. Glomalin, a SOM substance that may account for 20% of soil carbon, glues aggregates together and stabilizes soil structure making soil resistant to erosion, but porous enough to allow air, water and plant roots to move through the soil. Organic acids (e.g., oxalic acid), commonly released from decomposing organic residues and manures, prevents phosphorus fixation by clay minerals and improve its plant availability, especially in subtropical and tropical soils. An increase in SOM, and therefore total C, leads to greater biological diversity in the soil, thus increasing biological control of plant diseases and pests. Data also reveals that interaction between dissolved OC released from manure with pesticides may increase or decrease pesticide movement through soil into groundwater.

Specific problems that might be caused by poor function: A direct effect of poor SOC is reduced microbial biomass, activity, and nutrient mineralization due to a shortage of energy sources. In non-calcareous soils, aggregate stability, infiltration, drainage, and airflow are reduced. Scarce SOC results in less diversity in soil biota with a risk of the food chain equilibrium being disrupted, which can cause disturbance in the soil environment (e.g., plant pest and disease increase, accumulation of toxic substances).

What you can do: Compiled data shows that farming practices have resulted in the loss of tons of C from soils most of which is OC. To compensate for these losses, practices such as no-till may increase SOC. Other practices that increase SOC include continuous application of manure and compost, and use of cover crops. Burning, harvesting, or otherwise removing residues decreases SOC (Edwards et al., 1999).
Table 9.1.1. Size and breakdown rates of various soil organic matter fractions.

<table>
<thead>
<tr>
<th>Soil Organic Matter Fraction</th>
<th>Particle Size (mm)</th>
<th>Turnover Time (years)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>plant residues</td>
<td>≥ 2.0</td>
<td>&lt; 5</td>
<td>recognizable plant shoots and roots</td>
</tr>
<tr>
<td>particulate organic matter</td>
<td>0.06 – 2.0</td>
<td>&lt; 100</td>
<td>partially decomposed plant material, hyphae, seeds, etc</td>
</tr>
<tr>
<td>soil microbial biomass</td>
<td>Variable</td>
<td>&lt; 3</td>
<td>living pool of soil organic matter, particularly bacteria and fungi</td>
</tr>
<tr>
<td>Humus</td>
<td>≤ 0.0053</td>
<td>&lt; 100 – 5000</td>
<td>ultimate stage of decomposition, dominated by stable compounds</td>
</tr>
</tbody>
</table>
Any effective fertilizer recommendation program should be preceded by analysis of the soil physical, chemical and biological status. This forms the basis for preliminary fertilizer recommendations that should be validated using crop response trials. There exists a variety of methods that can be used to test various soil chemical properties.

These methods have developed over a long period of time through series of improvement to improve prediction effectiveness and reduce the time required to capture the results. Table 10.1 presents a summary of most common methods available for use in Kenya.

<table>
<thead>
<tr>
<th>Analytical method</th>
<th>Analyzed nutrient</th>
<th>Description</th>
<th>Nutrient Concentration range</th>
<th>Important points to note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro-Kjeldahl</td>
<td>Total Nitrogen</td>
<td>Extraction solution: H$_2$SO$_4$ conc. 96%, (Selenium (Se), copper sulphate hydrated (CuSO$_4$.5H$_2$O), potassium sulphate (K$_2$SO$_4$) or sodium sulphate (Na$_2$SO$_4$)-catalyst to raise the temperature. Titration reagents NaOH, 46%, Boric acid, H$_3$BO$_3$, 1%, 0.07144N H$_2$SO$_4$</td>
<td>&lt; 0.02% in sub-soils to &gt; 2.5% in peats. 0.06% - 0.5% in surface cultivated soils</td>
<td>Suitable for all soil types, determines organic and NH$_4$ Nitrogen. The aim of digestion procedure is to break all N bond in the sample and convert all the N into NH$_4$ ions. The Al block digester coupled with an efficient exhaust system is crucial for solving most of the environmental issues associated with classical Kjeldahl digestion system. The speed of the digestion process is dependent on the temperature used. The catalysts serves to increase the boiling point of H$_2$SO$_4$ hence increasing the digestion speed.</td>
</tr>
<tr>
<td>Devada’s alloy</td>
<td>Total Nitrogen + Nitrates</td>
<td>Macro-Kjeldahl + devada’s alloy</td>
<td>2- 5% of total N above</td>
<td>To include nitrate-N the use of devada’s alloy is necessary. Devada’s alloy is a reducing agent.</td>
</tr>
<tr>
<td>Total Phosphorus (P)</td>
<td>Total P in soils</td>
<td>4 methods used to determine total P in soils 1. Sodium carbonate fusion 2. Perchloric acid digestion 3. Sulphuric acid - hydrogen fluoride digestion 4. Sodium hypobromite oxidation and dissolution in sulphuric acid.</td>
<td>200 – 5000 mg P/kg</td>
<td>Methods # 2 and 4 may underestimate total P while methods # 1 and 3 may overestimate total P and are suitable for highly weathered soils that contain apatite &amp; high Fe oxides but cannot be used for routine analysis. Methods # 2 and 4 can be used for large number of samples.</td>
</tr>
</tbody>
</table>

Table 10.1 Different methods used in soil wet chemistry analysis (*Esther to clarify on the differences of the Mehlich and Bray methods*)
<table>
<thead>
<tr>
<th>Analytical method</th>
<th>Analyzed nutrient</th>
<th>Description</th>
<th>Nutrient Concentration range</th>
<th>Important points to note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olsen</td>
<td>Available Phosphorus</td>
<td>Extracting solution is 0.5M NaHCO₃, pH 8.5. Extraction takes 30 minutes. Colour development takes 1 hr; Soil/Reagent ratio: 1:20.</td>
<td>Critical range: 5 mg P/kg in clay soil - 10 mgP/kg in sandy soils.</td>
<td>Suitable for alkaline soils, which have high CEC and high base saturation.</td>
</tr>
<tr>
<td>Mehlich I</td>
<td>Available Phosphorus, Potassium, Calcium, Magnesium</td>
<td>Extraction solution is 0.05 N HCl + 0.025 N H₂SO₄. Solution/Reagent ratio: 1:4. Time of extraction is 5 minutes. Colour development is 1 hr.</td>
<td>10 mg P/kg in clay soils - 25 mg/kg in sandy soils.</td>
<td>Suitable for highly weathered characterized by low CEC, acidic soils. It is good extractant of calcium sulphate and extracts some Al-P but not as effectively as Ca-P. In soils where Rock-P has been applied care should be taken in using this extractant because it will dissolve some unreacted rock phosphate resulting in over estimation of the P supply and under estimation of the fertilizer P requirement. Therefore separate calibration curves are needed for soluble and phosphate rock based fertilizers.</td>
</tr>
<tr>
<td>Mehlich II</td>
<td>Phosphorus, Potassium, Calcium, Magnesium</td>
<td>0.2 N CH₂COOH + 0.2 NH₄Cl + 0.015 N NH₄F + 0.012 N HCl. Solution/Reagent ratio: 1:10. Time of extraction is 5 minutes. Colour development is 1 hr.</td>
<td>10 mg P/kg in clay soils - 25 mg/kg in sandy soils.</td>
<td>0.015 N NH₄F is a strong extractant of P.</td>
</tr>
<tr>
<td>Mehlich III</td>
<td>Phosphorus, Potassium, Calcium, Magnesium</td>
<td>0.2 N CH₂COOH + 0.2 NH₄NO₃ + 0.015 N NH₄F + 0.013 N EDTA. Solution/Reagent ratio: 1:10. Time of extraction is 5 minutes. Colour development is 1 hr.</td>
<td>10 mg P/kg in clay soils - 25 mg/kg in sandy soils.</td>
<td></td>
</tr>
<tr>
<td>Bray I</td>
<td>Phosphorus</td>
<td>Extraction solution 0.025 N HCl + 0.03 N NH₄F. Solution/Reagent ratio: 1:10. Time of extraction is 5 minutes. Time of colour development is 1 hr.</td>
<td>10 mg P/kg in clay soils - 25 mg/kg in sandy soils.</td>
<td>Is good for medium to high CEC soils, is a strong extractant of Al-P and also extracts some Ca-P due to acid decomposition. This extractant may also dissolve rock-P and therefore its use on soils where rock phosphate was applied is not recommended. One possible solution to this problem is to increase the HCl to 0.1 M as in the Bray II extractant and do two extraction on the same sample. The ray II extractant has the same concentration of NH₄F (0.03M) as the Bray I but the HCL has been increased to 1 M to give increased capacity to extract the lesser soluble Ca-P.</td>
</tr>
<tr>
<td>Bray II</td>
<td>Phosphorus</td>
<td>Extraction solution 0.1 N HCl + 0.03 N NH₄F. Solution/Reagent ratio: 1:17.</td>
<td>10 mg P/kg in clay soils - 25 mg/kg in sandy soils.</td>
<td>Is good for medium to high CEC soils, is a strong extractant of Al-P and also extracts some Ca-P due to acid decomposition. This</td>
</tr>
<tr>
<td>Analytical method</td>
<td>Analyzed nutrient</td>
<td>Description</td>
<td>Nutrient Concentration range</td>
<td>Important points to note</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------</td>
<td>-------------</td>
<td>-----------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Ana</td>
<td>Nutrient</td>
<td>Concentration range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time of extraction is 5 minutes. Time of colour development is 1 hr.</td>
<td></td>
<td></td>
<td></td>
<td>extractant may also dissolve rock-P and therefore its use on soils where rock phosphate was applied is not recommended. One possible solution to this problem is to increase the HCl to 0.1 M as in the Bray II extractant and do two extraction on the same sample. The bray II extractant has the same concentration of NH₄F (0.03M) as the Bray I but the HCl has been increased to 1 M to give increased capacity to extract the lesser soluble Ca-P.</td>
</tr>
<tr>
<td>Truog</td>
<td>Phosphorus</td>
<td>0.002 N H₂SO₄ buffered at pH 3 with (NH₄)₂SO₄</td>
<td>30 mg P/kg in clay soils –50 mg/kg in sandy soils</td>
<td>This sulphuric acid extractant is suitable for soils with high amounts of Fe and Al oxides or amorphous alumina-silicate clays, which react strongly with P making virtually unavailable for plant uptake.</td>
</tr>
<tr>
<td>Double acid and NH₄OAC</td>
<td>Potassium, Calcium, Magnesium</td>
<td>1. 0.05 M HCl in 0.0125 M H₂SO₄</td>
<td>K-100- 180 mg/kg Ca -1000- 1600 mg/kg Mg - 80- 100 mg/kg</td>
<td>The double acid extractant is suitable for sandy soils and acid soils with low CEC, whereas NH₄ extractant are suitable for a wide range of soils and are most commonly used in routine soil testing laboratories.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. 1 M NH₄OAC at pH 7 and 1 M NH₄OAC at pH 4.8</td>
<td>K-100- 180 mg/kg Ca- 1000- 1600 mg/kg Mg- 80- 100 mg/kg</td>
<td></td>
</tr>
</tbody>
</table>

**NB:** Mehlich1 should not be used to extract neutral or alkaline soils. When exposed to a neutral or alkaline pH soil, Mehlich1 rapidly loses effectiveness because the dilute acids are effectively neutralized. Mehlich1 is also rendered ineffective in soils with high cation exchange capacity (CEC), high Al and Fe accumulation, and high organic matter (>5%) content. Adolf Mehlich - while working in North Carolina Department of Agriculture during the 1950s and 1970s - developed the Mehlich-1, Mehlich-2, and Mehlich-3 series of soil extractants for the acidic soils, each one as an improvement over the previous in the sequence. While Mehlich-2 failed completely at the outset, Mehlich-1 and Mehlich-3 soil extractants were found effective (Mylavarapu et al 2014).

**Soil nutrient critical levels**

Soil nutrient deficiencies are a common occurrence across the world. Nutrient deficient soils cannot support optimal crop production. For certain nutrients the crops may grow normally, but consumption of such crops predisposes human being and animals to human and animal nutrition challenges. For example, whereas Zn deficiencies may not have a significant influence on crop yield, deficiency of Zn in the grain results in poor diet that leads to various Zn deficiency related body challenges. These deficiencies are correctable by use of fertilizers and other soil amendments. This is best done after soil diagnosis. Table 10.2 presents the indicators of deficiency, adequacy and excessive levels ranges of common soil nutrients from Mehlich I method.
### Table 10.2: Soil Critical Nutrient Levels:

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Deficiency level</th>
<th>Adequate level</th>
<th>Excessive level</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium, me%</td>
<td>seldom applies</td>
<td>0.2-2.0</td>
<td>&gt; 2.0</td>
<td>Excessive levels in saline &amp; sodic soils</td>
</tr>
<tr>
<td>Potassium, me%</td>
<td>&lt; 0.24</td>
<td>0.24-1.5</td>
<td>&gt; 1.5</td>
<td></td>
</tr>
<tr>
<td>Calcium, me%</td>
<td>&lt; 2.0</td>
<td>2.0-15.0</td>
<td>&gt; 15.0</td>
<td></td>
</tr>
<tr>
<td>Magnesium, me%</td>
<td>&lt; 1.0</td>
<td>1.0-3.0</td>
<td>&gt; 3.0</td>
<td></td>
</tr>
<tr>
<td>Phosphorus, ppm</td>
<td>&lt; 30</td>
<td>30-80</td>
<td>&gt; 80</td>
<td></td>
</tr>
<tr>
<td>Manganese, me%</td>
<td>&lt; 0.11</td>
<td>0.11-2.0</td>
<td>&gt; 2.0</td>
<td>For flowers</td>
</tr>
</tbody>
</table>

**TOTAL NITROGEN & CARBON**

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Deficiency level</th>
<th>Adequate level</th>
<th>Excessive level</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total nitrogen, %</td>
<td>&lt; 0.2</td>
<td>0.2-0.5</td>
<td>&gt; 0.5</td>
<td></td>
</tr>
<tr>
<td>Total organic carbon %</td>
<td>&lt; 1.33</td>
<td>2.66-5.32</td>
<td>&gt; 5.32</td>
<td>1.33-2.65 moderate level</td>
</tr>
</tbody>
</table>

**EXTRACTION WITH 0.1 M HCl**

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Deficiency level</th>
<th>Adequate level</th>
<th>Excessive level</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper, ppm</td>
<td>&lt; 1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron, ppm</td>
<td>&lt; 10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc, ppm</td>
<td>&lt; 5.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**OLSEN METHOD**

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Deficiency level</th>
<th>Adequate level</th>
<th>Excessive level</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus, ppm</td>
<td>&lt; 10</td>
<td>10.0-20.0</td>
<td>&gt; 20.0</td>
<td></td>
</tr>
</tbody>
</table>

### Table 10.3: Soil Test Interpretation for Mehlich-3 Extraction Method

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>LOW</th>
<th>MEDIUM</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>≤25</td>
<td>26–45</td>
<td>&gt;45</td>
</tr>
<tr>
<td>K</td>
<td>≤35</td>
<td>36–60</td>
<td>&gt;60</td>
</tr>
<tr>
<td>Mg</td>
<td>≤20</td>
<td>21–40</td>
<td>&gt;40</td>
</tr>
</tbody>
</table>

### Table 10.4: Comparison of Mehlich-1 and Mehlich-3 soil extractants (lets have the three mehlich methods)

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Mehlich-1</th>
<th>Mehlich-II</th>
<th>Mehlich-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valid pH Range</td>
<td>pH &lt; 6.5</td>
<td>Most normal soil ranges???</td>
<td>Fluoride facilitates dissociation of phosphates from Fe and Al oxides</td>
</tr>
<tr>
<td>Extraction of P</td>
<td>Limited in soils with high Fe and Al accumulations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction of Micronutrients</td>
<td>Dilute acid mixture, only some micronutrients extracted (specific micronutrients)</td>
<td>EDTA (chelate) extracts micronutrients (specific micronutrients)</td>
<td></td>
</tr>
<tr>
<td>Exchangeable Cations</td>
<td>Poor extractant for high CEC soils</td>
<td></td>
<td>Ammonium nitrate extracts exchangeable cations</td>
</tr>
</tbody>
</table>

77
There are three important principles inherent in all experimental designs that are essential to the objectives of statistical analysis:

1. Replication: it means that a treatment is repeated two or more times. Its function is to provide an estimate of experimental error and to provide a more precise measure of treatment effects. The number of replications that will be required in a particular experiment depends on the magnitude of the differences you wish to detect and the variability of the data with which you are working. Considering these two things at the beginning of an experiment will save much frustration.

2. Randomization: It is the assignment of treatments to experimental units so that all units considered have an equal chance of receiving a treatment. It functions to ensure unbiased estimates of treatment means and experimental error.

3. Local control: This principle of experimental design allows for certain restrictions on randomization to reduce experimental error. For example in the randomized complete block design, treatments are grouped into blocks that are expected to perform differently, allowing a block effect to be removed from total variation in the trial.

Meta data collection
Analytical data must always be supported with meta-data. The meta-data helps to describe a data set in a way that controls confusion especially if the data was to be stored for a long time or transferred from one analyst to another. It is also crucial for interpretation of the data. A good meta-data should provide a background that answers the question when, why, how, where, what and by who. The sections below give a detailed description of what should be included in the meta-data

Site description:
Study site name (county, sub-county, location, sub-location, village), agro-ecological zone, GPS coordinate, altitude, average temperature (°C), rainfall characteristic, average rainfall during trial, soil FAO classification, soil texture class, experiment design, treatments, test crop, sequence or rotation, type and quantity of fertilizer, crop varieties, number of reported seasons, years of trials, number of years of the study, number of replicates

Soils and agronomic data
Sampling depth (cm), initial soil data soil chemical (e.g Nitrogen (N), Phosphorus (P), potassium (K), Magnesium (Mg), Calcium (Ca), Cation exchange capacity (CEC)), physical (soil texture, bulk density) and biological (microbial biomass) properties and subsequent sampling soil data as above and the method of analysis used. Additionally, agronomic such as land preparation, planting fertilization, weeding, water management, crop or variety, net plot or harvest area (m²), no of rows, no of plants/stand count, no. of cobs, total cob fresh weight (kg) of cobs, stovers, fresh weight (g) sub-samples of cob, stover, dry weight sub-samples of cobs, stover and grain. dry sub-sample weight is extrapolated to t/ha and economic (cost of inputs and value of outputs) data should be included.

For legacy data the following additional information should be included in the meta-data: region of study, data manager, Country of study, reference title, year published, main author, other authors, author institution, publication type and name, publisher, vol. chapter

11.1 How to prepare data for analysis
Field data should be transferred to appropriate spread sheets such as excel and organized for analysis. In the same way that it takes time to design and to carry out a good experiment, it also takes time to conduct an effective data analysis.

- The data collected in the trial must first be converted to commonly used units prior to analysis, for example from kg/plot to kg/acre or tons/ha.
- Much can be learned from simply looking over the data without using statistical methods.
- However, often it can be difficult to tell just by looking at the data whether any differences are due to random variation or to treatment effects.
- The data is thus entered into the computer and ensuring it is in a suitable format for analysis.
- Prior to actual analysis data is explored for various indicators of errors, omission and commission and
variability.

• Excel is a helpful program for inputting and analyzing data collected.

• Statistical analysis re-orders the data that were randomized in the field and performs mathematical computations to determine the probabilities that the differences were caused by normal variation or by the treatments.

• The results of the data analysis give you the basis for making conclusions on the effects of the treatments.

• Analyses can be performed using different confidence levels. Most of the agricultural and natural resource researchers typically use a 95% confidence level, which means that there is a 95% chance that the measured differences are due to the treatments rather than to random variation or error.

• In reality, you will never be 100% sure that you have proved or disproved your hypothesis. Statistics are based on tendencies and likelihoods, never on certainties.

• The probability level can feasibly range from 0.001 to 0.2 (0.1 - 20%), depending on the economic or environmental implication of choices between management options being tested, interactions with other management practices, the grower’s experience and other factors. A common statistical tool for tests is Least significant difference (LSD), which is calculated through standard analysis of variance (ANOVA) statistical analysis software or can be calculated by hand. The SED and LSD are usually only suitable for balanced designs. For balanced designs 5% LSD ≈ 2×SED and SED = \sqrt{2 \times SE} \approx (one and a half) x SE.

• The LSD is a calculation based on the variability of treatment results within the trial and is used to help separate the effects of natural field variability from the treatment effects.

• If the difference between treatment means in a trial is equal to or larger than the LSD, the difference is statistically significant and believed to be due to the

<table>
<thead>
<tr>
<th>Plot</th>
<th>Treatment Description (e.g)</th>
<th>Crop/Variety</th>
<th>Grain Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maize/Desmodium</td>
<td>IR -Maize</td>
<td>1.5</td>
</tr>
<tr>
<td>1</td>
<td>Maize/Desmodium</td>
<td>IR -Maize</td>
<td>2.7</td>
</tr>
<tr>
<td>1</td>
<td>Maize/Desmodium</td>
<td>IR -Maize</td>
<td>3.6</td>
</tr>
<tr>
<td>1</td>
<td>Maize/Desmodium DK8031</td>
<td>DK8031</td>
<td>1.5</td>
</tr>
<tr>
<td>1</td>
<td>Maize/Desmodium DK8031</td>
<td>DK8031</td>
<td>4.7</td>
</tr>
<tr>
<td>1</td>
<td>Maize/Desmodium DK8031</td>
<td>DK8031</td>
<td>3.9</td>
</tr>
<tr>
<td>1</td>
<td>Maize/Desmodium DK8031</td>
<td>DK8031</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>Maize/ Double row gnuts</td>
<td>IR -Maize</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>Maize/ Double row soya</td>
<td>IR -Maize</td>
<td>3.8</td>
</tr>
<tr>
<td>2</td>
<td>Maize/ Double row gnuts</td>
<td>IR -Maize</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>Maize/ Double row beans</td>
<td>IR -Maize</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>Maize/ Double row beans</td>
<td>DK8031</td>
<td>5.1</td>
</tr>
<tr>
<td>2</td>
<td>Maize/ Double row beans</td>
<td>DK8031</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>Maize/ Double row beans</td>
<td>DK8031</td>
<td>5.3</td>
</tr>
<tr>
<td>2</td>
<td>Maize/ Double row beans</td>
<td>DK8031</td>
<td>4.4</td>
</tr>
<tr>
<td>3</td>
<td>Maize/ single row gnuts</td>
<td>IR -Maize</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>Maize/ single row soya</td>
<td>IR -Maize</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td>Maize/ single row gnuts</td>
<td>IR -Maize</td>
<td>4.6</td>
</tr>
<tr>
<td>3</td>
<td>Maize/ single row beans</td>
<td>IR -Maize</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>Maize/ single row beans</td>
<td>DK8031</td>
<td>3.1</td>
</tr>
<tr>
<td>3</td>
<td>Maize/ single row gnuts</td>
<td>DK8031</td>
<td>4.9</td>
</tr>
<tr>
<td>3</td>
<td>Maize/ single row beans</td>
<td>DK8031</td>
<td>4.7</td>
</tr>
<tr>
<td>3</td>
<td>Maize/ single row beans</td>
<td>DK8031</td>
<td>4.9</td>
</tr>
</tbody>
</table>
treatment effect and not natural field variability.
- On the other hand, if the difference between treatment means is smaller than the LSD, the differences are more likely due to natural field variability.
- The LSD is only used if the ANOVA analysis determines that treatment differences are significant.

**Results of Statistical Analysis**

In formal scientific papers it is often necessary to present results of statistical analyses.

They can indicate either the precision of the results, give further description of the data or demonstrate the statistical significance of comparisons.

Where statistical significance is referred to in text, the reference should be included in such a way as to minimize disruption to the flow of the text. Significance probabilities can either be presented by reference to conventional levels, e.g. \( P < 0.05 \) or, more informatively, by stating the exact probability, e.g. \( P = 0.023 \), usually derived from statistical packages. An alternative to including a large number of statements about significance is to include an overall covering sentence at the beginning of the results section, or some other suitable position. An example of such a sentence is: “All treatment differences referred to in the results are statistically significant at least at the 5% level unless otherwise stated.”

**Descriptive Statistics**

When simply describing a set of data with summary statistics, useful statistics to present are the mean, the number of observations and a measure of the variation or “scatter” of the observations, as well as the units of measurement. The range or the standard deviations (SD) are useful measures of the variation in the data. The standard error (SE) is not relevant in this context, since it measures the precision with which the mean of the data estimates the mean of a larger population. If there are a large number of variables to be described the means, SDs etc. should be presented in a table. However if there are only one or two variables, these results can be included in the text. For example:

“The initial weights of 48 ewes in the study had a mean of 34.7 kg and ranged from 29.2 to 38.6 kg.” or “The mean initial weight of ewes in the study was 34.7 kg (\( n = 48, \text{SD} = 2.61 \)).”

When quoting a standard deviation (or standard error), a ` sign is irrelevant. As well as being unnecessary here, a ` sign is ambiguous if used without explanation in expressions such as “Mean = 34.7 ± 3.6 kg”. It is not clear whether the number after the ` sign is a standard deviation, a standard error or a confidence interval.

**Results of Analyses of Variance**

The analysis of variance tables are primarily to help the scientist and are not normally included in a report. An exception is a specialized analysis where the individual mean squares are important in their own right. In such cases, the degrees of freedom and expected mean squares are presented. In most situations, the only candidates from the analysis of variance table for presentation are the significance probabilities of the various factors and interactions and sometimes the residual variance or standard deviation. When included, they should be within the corresponding table of means, rather than in a separate table.

In general, authors should present relevant treatment means, a measure of their precision, and maybe significance probabilities. The treatment means are the primary information to be presented, with measures of precision being of secondary importance. The layout of the table should reflect these priorities; the secondary information should not obscure the main message of the data. The layout of tables of means depends, as is shown below, on the design of the experiment, in particular on:

- Whether the design is balanced i.e. equal numbers of observations per treatment;
- Whether the treatments have a factorial structure;
- For factorial designs, whether or not there are interactions.

**Measures of Precision**

The measure of precision should be either a standard error of a mean (SE), or a standard error of the difference between two means (SED), or least significant difference (LSD). In the latter case, the significance level used should be stated, e.g. 5% LSD. The SED and LSD are usually only suitable for balanced designs.

For balanced designs 5% LSD ≈ 2 × SED and SED = \( \sqrt{2} \times SE \approx (\text{one and a half}) \times SE \).

- Only one of these three statistics is necessary and it
Table Analysis of variance for grain yield (t/ha)

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>d.f.</th>
<th>s.s.</th>
<th>m.s.</th>
<th>v.r.</th>
<th>F pr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety</td>
<td>1</td>
<td>29.371</td>
<td>29.371</td>
<td>4.66</td>
<td>0.063</td>
</tr>
<tr>
<td>Treatment</td>
<td>3</td>
<td>7.927</td>
<td>2.642</td>
<td>0.42</td>
<td>0.744</td>
</tr>
<tr>
<td>Variety Treatment</td>
<td>3</td>
<td>2.027</td>
<td>0.676</td>
<td>0.11</td>
<td>0.954</td>
</tr>
<tr>
<td>Residual</td>
<td>8</td>
<td>50.464</td>
<td>6.308</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>89.789</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table of means

<table>
<thead>
<tr>
<th>Variety</th>
<th>DK8031</th>
<th>H624</th>
<th>KSTP94</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.00</td>
<td>4.29</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment</th>
<th>maiza+bean</th>
<th>maize+desmodium</th>
<th>maize+groundnut</th>
<th>maize+soybean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety Treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DK8031</td>
<td>5.67</td>
<td>4.81</td>
<td>6.74</td>
<td>5.35</td>
</tr>
<tr>
<td>KSTP94</td>
<td>7.62</td>
<td>5.83</td>
<td>7.98</td>
<td></td>
</tr>
</tbody>
</table>

is important to make it clear which is being used.

Standard error (SE) is the simplest and more preferred.

One can multiply by 1½ or 3 to give the SED or 5% LSD, and can use the SE for both balanced and unbalanced situations. However some scientists and journal editors may have strongly-felt preferences for SEDs or LSDs and there is no over-riding reason why they need change. Measures of precision are usually presented with one more decimal place than the means. This is not a strict rule. For example a mean of 74 with a standard error of 32 is fine, but a mean of 7.4, with a standard error of 0.3, should have the extra decimal place and be given as 0.32.

Table Standard errors of differences of means

<table>
<thead>
<tr>
<th>Table</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>rep.</td>
<td>6</td>
</tr>
<tr>
<td>d.f.</td>
<td>20</td>
</tr>
<tr>
<td>s.e.d.</td>
<td>1.234</td>
</tr>
</tbody>
</table>

Some researchers like to include the results of a multiple comparison procedure such as Fisher’s LSD. These are added as a column with a series of letters, (a, b, c, etc) where treatments with the same letter are not significantly different. Often, though, these methods are abused. The common multiple comparison procedures are only valid when there is no “structure” in the set of treatments, e.g. when a number of different plant accessions or sources of protein are being compared. Even in such cases we suggest the method of reporting the results should be to sort the treatments into descending order of means, sorting on the most important variable. In addition a single standard error or LSD is given in the balanced case, individual standard errors in the unbalanced case. A few authors, and the occasional journal editor, will have severe withdrawal symptoms if told that their multiple comparison results are not required. We suggest that the results from a multiple comparison procedure are additional to, and not a substitute for, the reporting of the standard errors. If scientists find that the presence of multiple comparisons is helpful for them to write the text, then they can be included in the table at the draft stage. Once the text is written the tables should be reexamined. In most cases, the columns of letters almost never correspond to any of the objectives of the research and hence are not evident in the reporting of the results.
Then if the multiple comparison columns are not referred to within the text, as is often the case, the tables can be simplified by eliminating them.

11.2 Data presentation

Data can be presented in the text, in a table, or pictorially as a chart, diagram or graph. Text alone should not be used to convey more than three or four numbers. Sets of numerical results should usually be presented as tables or pictures rather than included in the text. Well presented tables and graphs can concisely summarize information which would be difficult to describe in words alone. When whole numbers (integers) are given in text, numbers less than or equal to nine should be written as words, numbers from 10 upwards should be written in digits. When decimal numbers are quoted, the number of significant digits should be consistent with the accuracy justified by the size of the sample and the variability of the numbers in it. In general, tables are better than graphs for giving structured numeric information, whereas graphs are better for indicating trends and making broad comparisons or showing relationships. Tables and graphs should, ideally, be self-explanatory. The reader should be able to understand them without detailed reference to the text, on the grounds that users may well pick things up from the tables or graphs without reading the whole text. The title should be informative, and rows and columns of tables or axes of graphs should be clearly labeled. On the other hand, the text should always include mention of the key points in a table or figure: if it does not warrant discussion it should not be there. Write the verbal summary before preparing the final version of the tables and figures; to make sure they illuminate the important points. Descriptions of the numbers represented in a table or picture should be kept as simple as possible, while having sufficient detail to be useful and informative. As with the original data, it is important that summaries make clear what was measured, where the data were collected, when the data were collected, and the source in case the data are quoted from elsewhere. Statistical information, e.g. appropriate standard errors, is usually required in formal scientific papers. This may not be necessary in articles for a more general readership. Such statistical information should be presented in a way that does not obscure the main message of the table or graph. Similarly, “perspective” should not be added to two-dimensional charts and graphs, as it impedes quick and correct interpretation. Tabular output from a computer program is not normally ready to be cut and pasted into a report. For example, a well-laid-out table need never include grid lines.

Graphs and Charts

The two main types of graphical presentation of research results are line graphs and bar charts. Graphs can be small, so multiple plots can be presented on a single page or screen. Line graphs can show more detail than bar charts. They should be used when the horizontal axis represents a continuous quantity such as time spent weeding or quantity of fertilizer applied. When the horizontal axis is a qualitative factor - such as ethnic group, crop variety or source of protein - bar charts are natural. In this case, joining up corresponding points in a line graph clarifies which set the points belong to, but the lines themselves have no interpretive value. Many softwares are useful for plotting clear and detailed graphs. These include excel, R, sigma plots, terra plots, SPSS, etc.

Line Graphs

Line graphs are useful to display more than one relationship in the same picture, for example the response to fertilizer of three different varieties. While there is no general rule, graphs with more than four or five lines tend to become confusing unless the lines are well separated. In a graph with more than one line, different line styles (e.g. solid line, dashed line etc.), colours and/or plotting symbols (e.g. asterisks, circles etc.) should be used to distinguish the lines. In any set of line graphs, plotting symbols and line styles should be used consistently. Also, consider using the same scale on each graph, when comparisons are to be made across graphs.

Bar Charts

Bar charts display simple results clearly. They are not generally useful for large amounts of structured information. Since the horizontal axis represents a discrete categorisation, there is often no inherent order to the bars. In this case, the chart is clearer to read if the bars are sorted in order of height, e.g. the first bar represents the treatment with the lowest yield, the next bar displays the second lowest yield and so on (Fig.11.2.1.). The opposite direction, ascending order, can also be used. This advice has to be compromised when there is a series of charts with the same categories. In this case, it is usually preferable to have a consistent bar order throughout the series. Also in a series of bar charts, the shading of the different bars (e.g. black, grey, diagonal lines etc.) must
be consistent. It is frequently useful to “cluster” or group the bars according to the categories they represent, to highlight certain comparisons. The method of grouping should be determined by the objective of the chart. It is easier for readers to make comparisons between adjacent bars than between distant bars, and the chart should be laid out accordingly. The figure below shows how bars can be placed together for purposes of comparison by treatment and site.

**Fig. 11.2.1. Fertilizer Effect on Yield of Maize-Pigeon pea Intercrop in Tanzania**

**Tables**

Demonstration tables are intended to be assimilated quickly by the reader or viewer. They should be clear and well-presented, using reasonable approximations to reduce numbers to relatively few significant digits. Over-large demonstration tables are intimidating and users tend to give up on them. If the information is all necessary, it should be split into manageable components. Omit any column which can be readily calculated from data in other columns. Minor, or not very relevant, categories can be combined. The orientation of a table can have considerable influence on the readability. It is much easier for a reader to make comparisons within a column of numbers than within a row. Therefore if the purpose of a table is to demonstrate differences between treatments or groups for a number of variables, the groups should define the rows of the table and the variables should define the columns. The number of digits and decimal places presented in a table should be the minimum that is compatible with the purpose of the table. It is often possible to use as few as two significant digits. For example numbers such as 4.083 t/ha could often be better presented as 4.08 t/ha. The number of decimal places should be consistent for each variable presented.

**Note:** Means with the same letter in the same column are not significantly different at (P>0.05)

**Tables of Frequencies**

The simplest tables arising from surveys, or from coded qualitative information, are of counts or frequencies. If relatively large counts are to be compared in a table with several rows and columns, it is often helpful to present them as percentages: common ways to do this involve
Table Yields of grain maize under legume intercrops (t/ha)

<table>
<thead>
<tr>
<th>TREATMENT</th>
<th>Vihiga</th>
<th>Siaya</th>
<th>Kakamega South</th>
<th>Mumias</th>
<th>Overall Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize-bean</td>
<td>4.08b</td>
<td>4.89a</td>
<td>3.76b</td>
<td>6.12a</td>
<td>4.77a</td>
</tr>
<tr>
<td>Sole maize (no fert.)</td>
<td>1.16a</td>
<td>2.88b</td>
<td>0.9b</td>
<td>0.31b</td>
<td>1.02b</td>
</tr>
<tr>
<td>Maize-groundnut</td>
<td>1.69a</td>
<td>4.13a</td>
<td>4.64a</td>
<td>6.82a</td>
<td>4.72a</td>
</tr>
<tr>
<td>Maize soybean</td>
<td>2.77a</td>
<td>3.7a</td>
<td>3.83a</td>
<td>5.94a</td>
<td>4.41a</td>
</tr>
<tr>
<td>Mean</td>
<td>2.68</td>
<td>3.9</td>
<td>4.14</td>
<td>6.32</td>
<td>4.6</td>
</tr>
<tr>
<td>LSD</td>
<td>3.46</td>
<td>1.69</td>
<td>1.37</td>
<td>1.54</td>
<td>1.36</td>
</tr>
<tr>
<td>CV</td>
<td>36.68</td>
<td>21.74</td>
<td>34.16</td>
<td>21.9</td>
<td>35.11</td>
</tr>
</tbody>
</table>

making the percentages add up to 100 across rows, or down columns, or across the whole table. These facilitate different types of comparison, and a careful choice should be made. The sizes of sample on which a percentage table is based should be made explicit.

Table Benefit: cost ratios of ISFM in Western Kenya

<table>
<thead>
<tr>
<th>Benefit/cost (Ksh.)</th>
<th>Maize-bean</th>
<th>Maize-groundnut</th>
<th>Maize soyabean</th>
<th>Sole maize</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>85860</td>
<td>84960</td>
<td>79380</td>
<td>16524</td>
</tr>
<tr>
<td>Legumes</td>
<td>10800</td>
<td>5670</td>
<td>2880</td>
<td>0</td>
</tr>
<tr>
<td>Total Revenue</td>
<td>96660</td>
<td>90630</td>
<td>82260</td>
<td>16524</td>
</tr>
<tr>
<td>Variable Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legume seed</td>
<td>3750</td>
<td>8250</td>
<td>6562.5</td>
<td>0</td>
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<tr>
<td>Harvest</td>
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<td>9063</td>
<td>8802</td>
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<tr>
<td>Shelling+Threshing</td>
<td>17712</td>
<td>17370</td>
<td>16452</td>
<td>3304.8</td>
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<tr>
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<tr>
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<td>39444</td>
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<td>39754.5</td>
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<tr>
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<td>47451</td>
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<td>7435.8</td>
</tr>
<tr>
<td>Benefit/cost ratio (BCR)</td>
<td>2.45</td>
<td>2.10</td>
<td>2.07</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Economic analysis

Beyond biophysical and chemical analysis economic analysis is important. Economic analysis is crucial for determination of returns on investment. There are several parameters that are used as a measure of return on investment. They include, but not limited to the value cost ratio and the benefit cost ratio. Benefit cost ratio is the most common measure of return on investment. It gives the ratio of benefits against the costs. Examples of gross benefits include the monitory returns after sale of the crop output. On the other hand the cost include the cost of labor, cost of inputs, and transport cost. Data for benefit cost ratio analysis can be derived from market survey or direct recording of costs or prices of various items or services related to production. Table presents a case of benefit cost ratio for and intercropping trial in western Kenya.

11.3 Data storage and retrieval

There are several basic types of information-storage-and-retrieval systems. Database systems store the information as a series of discrete records that are, in turn, divided into discrete fields (e.g., name, address, and phone number); records can be searched and retrieved on the basis of the content of the fields. The data are stored within the computer, either in main storage or auxiliary storage, for ready access. There are many different factors to consider when expanding your computer data storage capacity by means of external hard drive storage. These include storage capacity, cost, and ease of use, convenience, and cost efficiency, access to data, data safety, and maintenance.

Here are some of the data storage devices

1. External Hard Drive
2. USB Flash Drive
3. Re-writable CD/DVD
4. Cloud Storage / Online Backup (Internet)
5. Tape
A report is a short, sharp, concise document which is written for a particular purpose and audience. It generally sets out and analyses a situation or problem, often making recommendations for future action. It is a factual paper, and needs to be clear and well-structured. The precise form and content of a report will vary between organization and departments and in study between courses, from tutor to tutor, as well as between subjects.

Scientific reports that use qualitative research methods (e.g. interviews, participant observation, and textual analysis) may be less formally structured, although all seek to answer the same questions as a quantitative research report.

### 12.1 Developing a title

The title of your report should be concise and informative and encapsulate the essence of the research. It should not be vague and general. It should clearly and briefly indicate what the report is about. It can use maximal capitalisation and never a complete sentence, while articles (a, an, the) are usually omitted. It is usually less than 50 characters and should be at the top of the page.

**Titles should:**
- Describe contents clearly and precisely, so that readers can decide whether to read the report
- Provide key words for indexing

**Titles should NOT**
- Include wasted words such as “studies on,” “an investigation of”
- Use abbreviations and jargon
- Use “cute” language

### 12.2 The executive summary or abstract

The executive summary or abstract, for a scientific report, is a brief summary of the contents. It’s worth writing this last, when you know the key points to draw out. It should not be more than half a page to a page in length. The executive summary is designed to give busy ‘executives’ a quick summary of the contents of the report. A reader should be able to grasp the full scope and significance of the work reported without having to read the entire report. It includes a statement of the aim or objective of the experiment, a short description of the method used, the main results, and the conclusions or implications of the results. The abstract should normally be a single paragraph between 100 and 300 words.

The guidelines below address issues to consider when writing an abstract

a. What is the report about, in miniature and without specific details?
   - State main objectives. (What did you investigate? Why?)
   - Describe methods. (What did you do?)
   - Summarize the most important results. (What did you find out?)
   - State major conclusions and significance. (What do your results mean? So what?)

b. What to avoid:
   - Do not include references to figures, tables, or sources.
   - Do not include information not in report.

Additional tips:
- Find out maximum length (may vary from 50 to 300+ words).
- Extract key points from each section. Condense in successive revisions.

### 12.3 Table of contents

When a report is longer than five pages a table of contents should be included as it assists the reader to locate information quickly. It also gives the reader a schematic overview of the structure and contents of the report. It should include all section headings and subheadings and on its own page.

Depending on the report, the following can be included in the table of contents:

- **List of Figures** (optional, separate page)
  - This list is used mainly for reports containing numerous figures. It includes the figure number, caption and page number, ordered as they appear
12.4 The introduction

It discusses the theoretical background to the investigation and places the present work in context. Should include a literature review, which provides general background information about what has already been published in your research area. It should start broadly within your field, putting your topic into a wider context in order to orient your reader, and then quickly and briefly focus on your specific research problem. This provides adequate information about your research area, so that readers do not need to refer to other materials to understand your research problem. The aims of the present study should be clearly stated at the end of the introduction. It sets out what you plan to say and provides a brief summary of the problem under discussion. It should also touch briefly on your conclusions.

The following are subtitles than appear in the introduction

What is the problem?
• Describe the problem investigated.
• Summarize relevant research to provide context, key terms, and concepts so your reader can understand the experiment.

Why is it important or justification?
• Review relevant research to provide rationale. (What conflict or unanswered question, untested population, untried method in existing research does your experiment address? What findings of others are you challenging or extending?)

What solution (or step toward a solution) do you propose?
• Briefly describe your experiment: hypothesis (es), research question(s); general experimental design or method; justification of method if alternatives exist.

Additional tips:
1. Move from general to specific: problem in real world/research literature --> your experiment.
2. Engage your reader: answer the questions, “What did you do?” “Why should I care?”
3. Make clear the links between problem and solution, question asked and research design, prior research and your experiment.
4. Be selective, not exhaustive, in choosing studies to cite and amount of detail to include. (In general, the more relevant an article is to your study, the more space it deserves and the later in the Introduction it appears.)
5. Ask your instructor whether to summarize results and/or conclusions in the Introduction.

The introduction ends with a statement of specific hypothesis or hypotheses. This statement of the hypothesis should logically follow on from literature review and make an explicit link between the variables you are manipulating or measuring in your study and previous research.

12.5 Materials and methods

The purpose of this section is to precisely describe method and materials used to conduct the experiment with enough detail so that someone else can repeat the same procedure. It includes all information required for an exact repetition of the work performed. Since it is work already done, it is customary to use the past passive tense.

This section should be chronological and informative, providing
• Details of the experimental design,
• Details of the controls used, including their purpose,
• Details of the data recording techniques,
• Exact quantities and purities of reagents,
• Technical specifications of the apparatus,
• Specific methods of the sample preparation,
• Accurate nomenclature,
- Precise details of any subjects/samples included in the study.
- Details of the sampling protocols
- Briefly explain the general type of scientific procedure step by step.
- Describe what materials, subjects, and equipment (chemicals, experimental animals, apparatus, etc.) used. (These may be sub-headed Animals, Reagents, etc.)

**Additional tips:**
1. Provide enough detail for replication. For a journal article, include, for example, genus, species, strain of organisms; their source, living conditions, and care; and sources (manufacturer, location) of chemicals and apparatus.
2. Order procedures chronologically or by type of procedure (sub-headed) and chronologically within type.
3. Use past tense to describe *what you did.*
4. Quantify when possible: concentrations, measurements, amounts (all metric); times (24-hour clock); temperatures (centigrade)

**What to avoid:**
1. Don’t include details of common statistical procedures.
2. Don’t mix results with procedures.

### 12.6 Results section
Consist of the main findings of the study drawing attention to the most significant aspects. It provides the reader with a factual account of the findings making them as comprehensible as possible. The results section should be kept brief and repetition of methods or results should be avoided. Any comment on the results should be quantitative, not just qualitative; that is, any comments should be backed up with data.

The following are some questions asked for effective results sections in scientific reports.

**What did you observe?**
- For each experiment or procedure:
- Briefly describe experiment without detail of Methods section (a sentence or two).
- Report main result(s), supported by selected data:
- Representative: most common
- Best Case: best example of ideal or exception

### 12.7 Tables and figures
The tables and figures, their titles and legends, and appropriate statistical analyses, gives clarity of the results before interpreting them. Tables, graphics and photos are placed immediately after where they are first referred to in the text. The reader should also be referred (by number) to the diagrams at the appropriate time in the text and the most important features pointed out to them. Tables, and graphics and photos (called figures), should be sequentially numbered. In large reports with many chapters, they are sequentially numbered in each chapter (i.e. for Chapter 2 you will begin from Table 2.1, Figure 2.1). Titles for tables are centred above the table. Titles for figures are centred below the graphic. The source of the table or figure should also be included. The source is usually in a smaller font (e.g. 10 point) and aligned on the left hand margin under a table, and under the title of a figure.

1. Decide which results to present, paying attention to whether data are best presented within the text or as tables or figures.
2. Limit the number of tables and figures to those that provide essential information that could not adequately be presented in the text.
3. Include only results which are relevant to the question(s) posed in the introduction, irrespective of whether or not the results support the hypothesis(es).
4. Design each table and figure to be understandable on its own, without reference to the text.
5. Number each figure and table in the order in which they are referred to in the text (figures and tables are numbered separately).
6. Organize the tables and figures in such an order that they tell a story.
7. Check with the targeted journal, but typically tables and figures are located on separate pages that follow the Reference section.
8. Make sure there is no page break in the middle of a table or figure. Do not wrap text around tables and figures.
9. Be sure all figures and tables are referenced in the text.
10. Obtain permission from the copyright holder (usually the publisher) and acknowledge the source, if you are including a table or figure that has already been published.
11. Write the table titles and figure legends in the past tense.
12. Provide information regarding what is presented in the table or figure in the table titles and figure legends, but not a summary or interpretation of the results.

12.8 Figures
Figures provide visual impact and therefore they are often the best way to communicate the primary finding. They are traditionally used to display trends and group results but can also be used effectively to communicate processes or to display detailed data in a simple way.
- Label each axis including units of measurement and clearly identify the data you are displaying (e.g. label each line in a graph).
- Legends should be listed in numerical order on a separate page and each figure on a separate page in numerical order.
- Should be of high image quality, with minimal pixelization.
- Do not include experimental details in the legend; these details should be included in the methods section.
- Photographs of subjects should be used only if written, informed consent was obtained prior to the taking of the photograph.
- Choose the correct figure format:
  - If independent and dependent variables are numeric, line diagrams or scatter grams,
  - If only the dependent variable is numeric, bar graphs,
  - For proportions, bar graphs or pie charts.

12.9 Discussion and conclusions
This is usually the most important section of the report. It should include comments on the results. It begins in the introduction with the theory related to the experiment, moves on to the work carried out in the Methods and Results sections and returns to general ideas in the Discussion by discussing whether the results obtained are, or are not, consistent with the theory. In many cases, it may be appropriate in the discussion to comment on the suitability of the method used in the experiment. The conclusions are usually included in the discussion, but they can be separated. If conclusions are separate, the discussion should be summarised and a comment made on the success, or otherwise, of the experiment. Discussion section has two fundamental aims:
- To explain the results of your study,
- To explore the significance of your study’s findings.

Therefore there is need to:
- Interpret and explain the results;
- Examine whether and how the questions raised in the introduction section have been answered;
- Show how the results relate to the literature;
- Qualify and explore the theoretical importance/significance of the results;
- Outline any new research questions or areas for future research that the results have suggested.

The discussion is also the place in a report where any qualifications or reservations about the research should be aired. Statistically significant results still require analysis and discussion.

Consider questions like:
- How generally do the results apply?
- How close to real life are the variables manipulated in a laboratory situation?
- Were there any defects in experimental design or procedure?
- Were there any confounding factors in the design: could some other factor explain the results?

What do the observations mean?
Summarize the most important findings at the beginning.

For each major result:
- Describe the patterns, principles, relationships the results show.
- Explain how the results relate to expectations and to literature cited in the Introduction. Do they agree, contradict, or are they exceptions to the rule?
• Explain plausibly any agreements, contradictions, or exceptions.
• Describe what additional research might resolve contradictions or explain exceptions.

How do results fit into a broader context?
• Suggest the theoretical implications of the results.
• Suggest practical applications of the results?
• Extend the findings to other situations or other species.
• Give the big picture: do the findings help us understand a broader topic?

Additional tips:
• Move from specific to general: the finding(s) --> literature, theory, and practice.
• Don’t ignore or bury the major issue. Did the study achieve the goal (resolve the problem, answer the question, support the hypothesis) presented in the Introduction?
• Make explanations complete.
• Give evidence for each conclusion.
• Discuss possible reasons for expected and unexpected findings.

What to avoid:
• Don’t over generalize.
• Don’t ignore deviations in the data.
• Avoid speculation that cannot be tested in the foreseeable future.

What conclusions can be drawn?
The conclusion sets out what inferences can be drawn from the information, including any experimental results. It may include recommendations, or these may be included in a separate section.

Recommendations suggest how the situation could be improved, and should be specific, achievable and measurable. If the recommendations have financial implications, set these out clearly, with estimated costs if possible.

12.10 Acknowledgements
The main purpose of the acknowledgements is to thank and recognize those who were directly involved in the study. Acknowledgments are about courtesy, where those who were directly, or were involved in supporting the work are appreciated. Do not confuse the acknowledgements section with a dedication - this is not where friends and relatives are appreciated unless they have helped in the study. Significant support from technicians, tutors, or other students and financial support are acknowledged here. This section should be very brief, a few lines at the most. Identify those who provided the most support, and thank them appropriately.
A referencing style is a set of rules telling you how to acknowledge the thoughts, ideas and works of others in a particular way. Referencing is a crucial part of successful academic writing and is key to research. It shows a list of all the sources cited and it is usually in an alphabetical order according to the names of the authors. Each entry in the reference list contains detailed information about one source. This usually includes the author’s name(s), the year of publication, the title of the article, and details of where the article is published. There are a number of softwares that support referencing e.g Zotero, endnote, etc.

Referencing is used to tell the reader where ideas from other sources have been used. These are some reasons why it is important to reference sources correctly:

- It shows the reader that other sources can be used to create a solid argument
- It properly credits the originators of ideas, theories, and research findings
- It shows the reader how the argument relates to the big picture

Referencing is needed when:

- You have copied words from a book, article, or other source exactly (quotation)
- You have used an idea or fact from an outside source, even if you haven’t used their exact wording (paraphrasing and summarizing)

There are two elements used in referencing:

- A citation inside the body of the assignment
- An entry in a reference list or bibliography at the end of the assignment

13.1 Reference Styles

A few of the common referencing styles are explained below:

**APA** (American Psychological Association)

APA stands for “American Psychological Association” and comes from the association of the same name. Although originally drawn up for use in psychological journals, the APA style is now widely used in the social sciences, in education, in business, and numerous other disciplines. APA is an author/date referencing system common in the social sciences; it uses parenthetical in-text citations to refer readers to the list of references at the end of the paper. Numbered notes or footnotes are reserved for extra explanatory information that would disrupt the continuity of the text. The date of the research is important in scientific disciplines, since it conveys how recent or indeed historical the material is, thus the author/’s last name and the year of publication appear within the text. Page numbers are used in the text only in the case of direct quotations, not for paraphrased material.

**Example**

Pinker (1999) notes that memory loss, including memory for words, is an obvious and early symptom of Alzheimer’s disease.

The alphabetical Reference List at the end of the paper provides the necessary information for readers to locate and retrieve any source cited in the body of the text. It lists alphabetically in this order: the last name of the author followed by the initials and the year of publication in brackets. In the case of a book with one author, the title of the book comes next, in italics, with just the initial letter of the first words of the title and subtitle capitalized. This is followed by the place of publication, and the name of the publisher. The information in the List of References must be detailed enough to enable the reader to easily locate the edition or volume or issue number, in the case of journals, or web page etc.

**Example**


**MLA** (Modern Language Association of America)

MLA comes from the “Modern Language Association of America” and is used mainly in English and the Humanities. The MLA system, common in the arts and humanities, is similar to APA in that it uses parenthetical in-text citations keyed to a list of works cited at the end of the paper. The author’s last name appears in the text close to the borrowed material along with a page number rather than the year. Literature and language rely more on exactly where in the text the quoted material can be
found, either directly quoted or paraphrased, rather than the year. Numbered notes or footnotes are only for extra information that would disrupt the continuity of the text. MLA is generally simpler and more economical than other styles; interruptions are kept to a minimum, usually citing just the last name of the author and the relevant page number within the text.

The List of Works Cited at the end of the paper provides the necessary information for readers to locate and retrieve any source cited in the body of the text. It lists alphabetically in this order: the last name of the author followed by the first names. In the case of a book with one author, the title of the book comes next, italicized, with the initial letter of each significant word in the title capitalized. This is followed by the place of publication, and the name of the publisher, the year of publication, and finally the medium.

Example

Chicago
Chicago is sometimes referred to as Turabian or Chicago/Turabian. It comes from the “Chicago Manual of Style” and the simplified version of it, “A Manual for Writers of Term Papers, Theses, and Dissertations”, that Kate Turabian wrote [Source: The Writing Center at the University of North Carolina at Chapel Hill]. Chicago is used mainly in the social sciences, including history, political studies, and theology. The Chicago notes-bibliography citation system, used by some humanities and social sciences, signals to the reader by a superscript number at the end of the sentence that a source has been used:

Example
According to Pinker, memory loss, including memory for words, is an obvious and early symptom of Alzheimer’s disease.1

The source of the quotation and information about the author, title and publication details and the relevant page numbers are then cited in a correspondingly numbered footnote at the bottom of the page, or endnote at the end of the paper. If the text is cited again, the subsequent notes may be shortened. Although the same information appears in both the notes and the bibliography it serves two different functions: The notes supply a quick check of the source, and the bibliography illustrates the extent of the research and the relationship to earlier studies. Thus both notes and bibliography are usually provided. There are, however, slight differences in punctuation since the notes are designed to be read as text and the bibliography constitutes a list of independent entries. The author’s name appears in the notes as first name last name, Mickey Mouse, while the bibliography entry inverts them, Mouse, M.

Number all notes consecutively from 1. Substantive notes are inserted as appropriate within the list of footnotes.

Vancouver
Vancouver originally came from The International Committee of Medical Journal Editors which produced the “Uniform Requirements for Manuscripts Submitted to Biomedical Journals” following a meeting that was held in Vancouver in 1978 [Source: Jönköping University Library]. The Vancouver style is used mainly in the medical sciences.

Harvard
Harvard came originally from “The Bluebook: A Uniform System of Citation” published by the Harvard Law Review Association. The Harvard style and its many variations are used in law, natural sciences, social and behavioral sciences, and medicine. Note: All second and third lines in the APA Bibliography should be indented.

Ref. The University of York, Academic Integrity, Academic Integrity IEEE Referencing Style https://www.york.ac.uk/integrity/ieee.html, Last Updated: September 5, 2013 | integrity@york.ac.uk http://pitt.libguides.com/c.php?g=12108&p=64730

13.2 Appendices
The main purpose of the appendices is to present additional data that is too extensive to be included within the main body of the text. Appendices are not included in all scientific reports; however they are frequently included in the back of theses. For example, printouts of raw data or other supplementary materials may be included as appendices at the back of a thesis. Different types of material included in the appendices can be labeled as Appendix 1, Appendix 2, and so forth. Some electronic journals now offer scientists the opportunity to
include extra materials that are too extensive for the main body of a journal article in an ‘e-appendix’. Confirm the inclusion of appendices with your tutor or supervisor.

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</table>


Kenya Soil Health Consortium (KSHC),
P.O Box 14733-00800, KALRO- Kabete, Waityaki way, Nairobi,
www.kenya.soilhealthconsortium.org