Guideline for measuring agronomic gain key performance indicators in on-farm trials

Version 1

December 2022

Contents

Introduction

Agronomic gain key performance indicators (KPIs) are designed to monitor, evaluate and measure the impact of changes in agronomic practices in the CGIAR Excellence in Agronomy initiative (EiA). The current KPIs cover land productivity and its stability, resource use efficiency and soil health (Table 1; Saito *et al.*, 2021). It is expected that the KPIs will be used across geographies, farming systems, and research and development (R&D) stages to deliver a greater depth of understanding of agronomic gain than has ever been achieved before. This document provides a guideline for measuring agronomic gain KPIs in on-farm trials.

On-farm trials belong to the proof-of-concept stage, which involves the testing and assessment of improved agronomic practices and their impact on agronomic gain (Fig. 1). These trials are researcher managed, conducted in multiple environments. They compare local, current farmers' practices or recommended practices (control treatment) with alternative, improved practices that are expected to perform better and are introduced by researchers. These treatments are implemented in the same field, with plots arranged side by side, with the option of replicates within the same field. We will not consider on-farm trials in which improved agronomic practices are piloted or demonstrated in the entire field, without a valid control in the same field.

Ideally, all KPIs should be collected in all trials. However, early in the proof-of-concept stage (e.g. first year of testing), the final decision on which indicators will be collected at each site will be decided by the researchers, usually depending on available resources. Later, when improved agronomic practices are evaluated for their suitability to be moved to the next stage — specifically when moving from the 'proof-of-concept' or the 'pilot' to 'scaling' stages — the decision-making should be based on data on all indicators (Fig. 1). Only the full set of indicator data (yield, its stability, profitability, labor and capital demand, soil health, climate change adaptation etc.) will enable comprehensive estimation of agronomic gains of improved agronomic practices and prevent individual aspects or features of the improved practices hampering adoption.

After an introduction to KPIs, this document provides examples of agronomic gain KPI assessment. In the last section, we present frequently asked questions (FAQs) related to agronomic gain KPIs and their assessment.

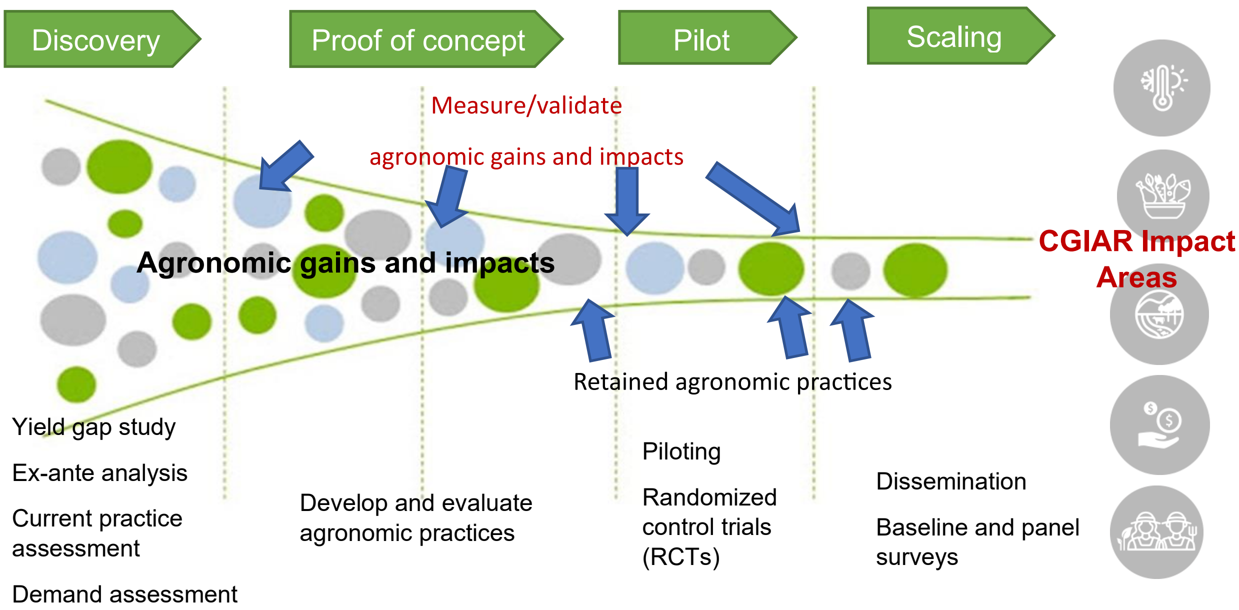

Figure 1. Agronomic gain KPI assessment along the four R&D stages

Each circle indicates a new agronomic practice. This figure indicates that in the staging process using KPI assessment, some of the agronomic practices will not move to the next stages, resulting in smaller number of agronomic practices in pilot and scaling stages than in proof-of-concept stage.

Table 1. Agronomic gain key performance indicators

KPI	Detailed indicator/description	Unit	Theory of change and link with impact areas and their collective global 2030 targets* in One CGIAR Research and Innovation Strategy 2030
Land productivity and its stability	Primary product harvested yield (referred to as yield)	kg/ha	Increased crop yield with low weather risk can lead to increased food security of smallholder farmers, an increase in market surplus and increased national food security (i), (ii), (iii), (iv)*
	Secondary product harvested yield	kg/ha	
	Yield stability (= Sustainable Yield Index)	Unitless	
	Profit or cost–benefit balance	US$/ha Local currency/ha	Increased profit leads to increased household capacity to pay for food, health services and education, and to invest in farming (i), (ii), (iii)
Resource use efficiency	Nutrient-use efficiency (e.g. nitrogen, phosphorus)	kg (yield†)/kg (nutrient input)	Improved nutrient-use efficiency with agronomic interventions can lead to increased yield or reduced input costs, higher profitability, increased food security, less nutrient loss to the environment, reduced greenhouse gas (GHG) emissions from fields (especially nitrogen), and reduced energy consumption in production and transportation of fertilizers (i), (ii), (iii), (iv), (v)
		kg (nutrient in yield†)/kg (nutrient input)	
	Water productivity	kg (yield†)/m^3 (water input [rainfall + irrigation])	Saved irrigation or rainwater can be used for other important purposes. Increased crop productivity with same or less water input can result in improved water productivity, leading to increased food security for smallholder farmers, an increase in market surplus and increased national food security (i), (ii), (iii), (iv), (v)
	Labor productivity	kg (yield†)/ work-day§	Increased labor productivity leads to increased profitability, more time to spend on other activities and increased willingness to invest in farming (i), (ii), (iii), (iv)
Soil health	Soil organic carbon (SOC)	g/kg	Building up SOC can lead to improved soil fertility and crop productivity, increased household resilience to climatic shocks, and contribute to climate change mitigation (i), (ii), (iii), (iv), (v)
	SOC stock (0–30 cm)	t C/ha	
	Partial carbon balance	kg/ha	

* (i) Nutrient, health and food security; (ii) poverty reduction, livelihood and jobs; (iii) gender equality, youth and social inclusion; (iv) climate adaptation and GHG reduction; and (v) environmental health and biodiversity.

† Yield can be primary and/or secondary harvested yield per hectare. The yield, nutrient-use efficiency, water productivity and labor productivity of the secondary product can be determined only when it has economic value in the action sites.

§ Typical working hours per work-day should also be reported.

Description of key performance indicators

1. Primary or secondary product harvested yield

This indicator measures total mass of primary or secondary product harvested per hectare (referred to as yield). Whether primary product harvested yield only or both primary and secondary product harvested yield should be considered in KPI assessment will be based on farmers' main production objectives in the given target site. Any plant part that the farmers consider the main product can be the primary harvested product. In cereals, the product is usually the grain but in many other crops it can be planting material (e.g. stems of cassava, mini-tubers of yam, suckers of banana), while the same crop for another farmer has roots, tubers and bunches as primary products. The yield of the secondary product can be determined only when it has economic value in the target sites. Table 2 shows typical primary and secondary products. The agronomic gain in yield is the difference between yield obtained when applying improved agronomic practices and yield obtained with farmers' practices or the current recommendations.

1.1 Formulas

$$\text{Primary product harvested yield (kg/ha)} = \frac{\text{Total mass of primary product harvested (kg)}}{\text{Plot size (ha)}} \qquad (1)$$

$$\text{Secondary product harvested yield (kg/ha)} = \frac{\text{Total mass of secondary product harvested (kg)}}{\text{Plot size (ha)}} \qquad (2)$$

For each product the status has to be indicated as dry matter or fresh matter, or adjusted to specific moisture content (e.g. for rice, 14%). When the dry matter yield is quoted, the residual moisture content should also be indicated.

Table 2. Typical primary and secondary products of selected crops and their major uses

Crop	Primary product	Secondary product
Rice, wheat, barley, maize, sorghum, teff, cowpea, soybean	Grain (food)	Straw (fodder)
Potato	Tubers (food)	
Cassava	Roots (food)	Stems (planting material)
		Green leaves (food)
Yam	Tubers (food)	Tubers (planting material)
Banana	Bunches (food)	Suckers (planting material)
		Trunks and leaves (fodder and wrapping material, fiber)
Coffee, cacao	Beans (food or drink)	

1.2 Measurement

Detailed data collection processes and calculations are given in the standard operating procedures (SOPs) for determination of the harvested area and specific crops (see Table 2 and annex).

2. Yield stability

Yield stability refers to how stable the crop yield from adopting agronomic practices is over time (i.e. from one year to another). Agronomic practices with high yield stability will have smaller yield differences across years than the practices with low yield stability. There are many factors that affect yield stability, such as soil quality and the build-up of pests and diseases. Analyses of yield stability are also important in the context of increased weather variability and change. The latter requires measurement of yield in on-farm trials over at least 10 years. If such data are not available, an alternative option is to use on-station long-term trials data. When long-term yield data are not available, crop simulation models considering long-term climate data of that environment can be used to assess the impact of agronomic practices on yield stability over years. However, these will only work when there is a well-calibrated model for the specific sites at which the on-farm trials are conducted. Moreover, this approach has its limitations since the crop models only consider water- and nitrogen-limited crop productivity; other growth-limiting factors are not considered in most existing models. The agronomic gain in yield stability is the difference between the Sustainable Yield Index (SYI) obtained with improved agronomic practices and the current farmers' practices or the latest recommendations.

The SYI is a simple quantitative measure to assess the sustainability of agronomic practices. It assesses the stability of yield over (a long period of) time. A low value of standard deviation (SD) suggests sustainability of the system. Conversely, if SD is large, SYI will be low indicating unsustainable management practices. The index values are between 0 and 1.

2.1 Formula

The SYI is calculated as a quantitative measure to assess the sustainability of the improved agronomic practice on the basis of average variability in yield – see equation (3).

$$SYI_i = \frac{Y_{mean,i} - SD_i}{Y_{max}} \qquad (3)$$

where, Y_{mean} is the mean yield over a number of years/seasons for agronomic practice i; SD is the standard deviation of the yield, over a number of years/seasons; and Y_{max} is the maximum yield obtained with the agronomic practice i. Here, 'yield' can be primary product harvested yield alone, or both primary and secondary product harvested yield. In the latter case, these two should be analyzed separately.

2.2 Measurement

Detailed data collection processes and calculations are given in the standard operating procedures (SOPs) for determination of the harvested area and specific crops (see Table 2 and annex).

3. Profit or cost–benefit balance

The next indicator of agronomic gain in land productivity and its stability is the improvement of cost–benefit balance. The agronomic gain in profit or cost–benefit balance is the difference between the balance under improved agronomic practices and that obtained under farmers' practices or current recommendations.

3.1 Formulas

Cost–benefit balance = Gross revenue – Total production cost (4)

Gross revenue = [(Primary product harvested yield) x (Primary product harvested sale price)]
+ [(Secondary product harvested yield) × (Secondary product harvested sale price)] (5)

Primary and secondary product harvested sale price is expressed in US$/kg or local currency/kg. Cost–benefit balance, gross revenue and total production cost are expressed in US$/ha or local currency/ha.

The agronomic gain in cost–benefit balance can be calculated as per formula (6).

Agronomic gain in cost–benefit balance = Harvested product price × Δ Yield – Δ Production cost (6)

Where Δ yield (expressed in kg/ha) is the increased (or reduced) yield with improved agronomic practices in comparison with the current farmer's yield, and Δ production cost (in US$/ha or local currency/ha) is the increased (or reduced) production cost induced by the use of improved agronomic practices. The agronomic gain in cost–benefit balance is expressed in US$/ha or local currency/ha.

Here, for agronomic gain in cost–benefit balance, we could focus on specific production costs, which depend on what kinds of improved agronomic practices are being introduced. If improved agronomic practices include fertilizer management, we consider the difference in the costs of fertilizers and their transportation, and labor inputs for fertilizer application and harvesting between improved agronomic practices and control only. For integrated agronomic practices (e.g. combination of tillage and herbicide etc., including labor-saving technologies), changes in labor, hiring machinery service, cost of herbicide, etc., should be considered as production costs.

3.2 Measurement

Apart from yield, additional data required include the sale prices of products in the experimentation year and production costs. These data can be collected through farm records in on-farm trials and information from markets.

4. Nutrient-use efficiency

Nutrient-use efficiency (NUE) can be defined as yield per unit of nutrient input (kg yield/kg nutrient applied) or as the output/input ratio of the nutrient (kg nutrient in yield/kg nutrient applied). An increase in NUE over time would be considered positive as there is no or low loss of applied nutrient, provided farmers do not mine their soil nutrient stocks. Nutrient mining can be assessed by using the output/input ratio of the nutrient. A ratio > 1 indicates that the soil nutrient stock is mined. However, this ratio should be used with caution as this approach considers neither all other nutrient inputs and losses, nor the amount of the specific nutrient stored in the soil. Where possible, NUE should be assessed over a long period, to serve as a meaningful indicator. It should also be kept in mind that when fertilizer application is small in farmers' fields and application rates are increased with the introduction of improved nutrient management practices, NUE often declines rapidly. Thus, to avoid misinterpretation of agronomic gain in NUE, the amount of nutrient input needs to be reported. Furthermore, if the fertilizer application rate is zero, the nutrient balance (= nutrient uptake in yield — input) should be used since the above two indicators cannot be computed when no nutrients are added. Finally, the choice of nutrients to be considered as KPIs depends on the local context.

4.1 Formulas

Here, we deal with the primary product harvested and nitrogen (N) as an example. The same can be done for other nutrients and secondary products harvested. The partial factor productivity (PFP), here for N (PFPN) is calculated as per formula (7).

$$\text{PFPN} = \frac{\text{Primary product harvested yield}}{N_{\text{inorganic fertilizer}} + N_{\text{organic input}}} \tag{7}$$

$$\text{Nitrogen-use efficiency} = \frac{N_{\text{output}}}{N_{\text{inorganic fertilizer}} + N_{\text{organic input}}} \tag{8}$$

$$\text{Nitrogen balance} = N_{\text{inorganic fertilizer}} + N_{\text{organic input}} - N_{\text{output}} \tag{9}$$

where PFPN is the partial factor productivity of applied N (kg/kg N); $N_{\text{inorganic fertilizer}}$ is the N applied to a crop via inorganic fertilizer (kg N/ha); $N_{\text{organic input}}$ is the N applied to the crop via organic input (kg N/ha); and N_{output} is the N content in yield (kg N/ha). N_{output} and the N balance is expressed in kg N/ha.

4.2 Measurement

Required data for this indicator are: (i) yield, (ii) nutrient content in yield (if formulas 8 and 9 are used), and (iii) the total amount of the applied nutrient (kg) of each type of fertilizer applied (organic and inorganic) during the entire crop duration. The assessment of yield is described in section 1. The amount of a specific nutrient applied as inorganic fertilizer can be calculated by the total fertilizer application rate multiplied by the nutrient concentration in the fertilizer. The nutrient content in yield and organic inputs needs to be determined in a laboratory, or estimated from existing data from previous studies, if the origins and conditions are sufficiently similar. Please see SOPs shown in the annex for crop cut and sample preparation for plant nutrient analysis.

5. Water productivity

Water productivity is defined as the total amount of yield per input of water (kg yield/m^3 water [rainfall + irrigation]). An increase over time would be considered desirable.

5.1 Formula

$$\text{Water productivity} = \frac{\text{Primary product harvested yield}}{\text{Total volume of irrigation water + Total volume of rainfall}} \tag{10}$$

Water productivity and total volume of irrigation water and rainfall per season are expressed in kg/m^3 water and m^3, respectively.

Formula (10) deals with the primary product harvested only. This can be also appliable to secondary product harvested.

This approach has limitations, as most agronomic interventions principally do not affect the amount of rainfall. In these cases, the yield obtained with different agronomic practices is the determinant of water productivity. In cases where the water management practices are investigated and different amounts of irrigation water are applied, both factors (yield and water volumes) are determinants of water productivity. In both cases, unproductive losses such as leaching and surface run-off are not considered and will be part of water input, resulting in lowering apparent water productivity. For example, this water productivity does not take into account changes in water storage in the root zone of the soil profile. With increased use of stored water over the growing season, an underestimation of the water productivity will result from the fact that more water is in the profile and this water is not consumed by the crop. In case the water storage declines during the growing season, an artificial overestimation of the water productivity would result from consumption of water that is not supplied by rain or irrigation. The proportion of evaporation is not considered either, despite the fact that some agronomic practices affect evaporation strongly. For example, introduction of no tillage together with mulch could improve water availability through reduced evaporation, but this is not considered in this calculation. In areas with a water balance of around zero or negative, the differences in water storage and evaporation might strongly affect the water productivity.

In high-rainfall areas with a positive water balance and unproductive water losses being inevitable, the amount of rainfall usually exceeds the actual evapotranspiration by a large amount. In such areas, water productivity might be considered less important, as agronomic practices are unlikely to target increased water use efficiency since water is a non-limited resource.

5.2 Measurement

Required data are: (i) yield, and (ii) water inputs, which are disaggregated by source — rainfall and irrigation. They should be collected from one month before planting until harvest. Rainfall (mm) is recorded using a rain gauge. An alternative option is to use rainfall data that can be sourced from local meteorological organizations or use global rainfall prediction models that are available through agencies such as the National Aeronautics and Space Administration (Sparks, 2018). The amount of irrigation water can be measured by installing a flow meter or calibrated pump, and recording the time when it is open for each irrigation event. In the case of rice flooded by irrigation, more detailed information on data collection on water inputs is available in SRP (2020). An SOP on measurement of irrigation water (under development) also provides various approaches to quantifying irrigated water input. If data on irrigation water cannot be determined in all the fields, data can be collected in randomly selected fields.

6. Labor productivity

Labor productivity is defined as kg of harvested yield per person-day worked. An increase over time would be considered desirable.

6.1 Formula

$$\text{Labor productivity} = \frac{\text{Primary product harvested yield (kg/ha)}}{\text{Total labor input (person-days/ha)}} \qquad (11)$$

Labor productivity and total labor input are expressed in kg/person-day and person-day/ha, respectively. If secondary product harvested yield is taken into account, primary product equivalent yield should be calculated for secondary products.

6.2 Measurement

Required data for this indicator are: (i) yield, and (ii) amount of total labor inputs disaggregated by sex, including the time required to transport all materials to the field site and all the required crop-related farm activities such as field clearing, tillage, seeding, planting, weeding, irrigation and fertilizer application, pest management, and harvesting and the transport of the products to the processing or sales point. Labor includes temporary, permanent and seasonal workers paid in cash as well as non-paid labor carried out by family members, other relatives and acquaintances. When cropping relatively small plots, labor inputs can be recorded on an hourly basis or by the minute in each plot to accurately assess labor at each level of intervention. In large-scale field trials with large plots, labor time should be measured by the hour and data collected through farm diary records. If the plot size is small, labor input might not be properly determined and value may be overestimated if research-related activities are included. However, the more likely risk is underestimation of the labor requirements because working in small plots is usually done in a short time and therefore a fatigue effect will not be observed as would be the case in very large fields, where any of the operations could take several hours. Generally, it can be assumed that labor data from large fields are more reliable than labor data from small plots.

7. Carbon input

The addition of organic inputs including manures, compost and retained crop residues including both above and below ground parts after harvest of a crop and during fallow periods is the main source for building up soil organic carbon (SOC) stocks. The magnitude of the effect on SOC content depends on the quantity and quality of organic inputs added, the physical and chemical properties, the weather conditions in each environment, and the soil biotic activity. The direct measurement of SOC content is based on wet oxidation or combustion of the soil such as in the Walkley Black method or dry combustion autoanalyzer (FAO, 2020a, b). Given that the SOC is a large pool relative to the small changes occurring due to organic matter additions and management, it is difficult to detect short-term changes in SOC content as a result of specific agricultural management practices. For the indirect assessment, we adopted carbon input, which focuses on the quantity of carbon (C) added to the soil from organic inputs. A special case is the addition of biochar, which stems from organic materials, has different chemical properties, but is not reacting in the soil in the same way as the materials from which it is created, due to its relatively strong inertia under chemical transformation and mineralization. However, if present in the soil and if analyzed by dry combustion CN analyzers, it will combust completely and can be expressed as soil organic matter (SOM). Biochar does not completely convert to measurable C if the analysis is performed using the Walkley Black method.

7.1 Formulas

$$\text{Input (kg C/ha)} = \frac{\text{Manure or compost (kg dry matter/ha)} \times \text{C concentration* of manure or compost (\%)}}{100}$$
$$+ \frac{\text{Retained aboveground crop residues (kg dry matter/ha)} \times \text{C concentration* of retained aboveground crop residues (\%)}}{100}$$
$$+ \frac{\text{Root dry mass of crop at harvest (kg dry matter/ha)} \times \text{C concentration* of roots of crop at harvest (\%)}}{100} \quad (12)$$

$$\text{Root dry mass (kg dry matter/ha)} = \frac{\text{Total dry aboveground dry mass (kg dry matter/ha)}}{\text{Shoot : root ratio*}} \quad (13)$$

Zero (0) should be used for root dry mass for root, tuber and perennial crops (see Table 3).

*Derived from crop-specific values from literature or previous study in action sites.

Table 3. Retained aboveground residues and existence of root residues of selected crops

Crop	Typical retained aboveground residues after harvesting of primary and secondary products	Existence of root residues as carbon input
Rice, wheat, barley, maize sorghum, teff	Straw (15–30 cm above ground will be retained)	Yes
Cowpea, soybean	Shed leaves and straw	Yes
Potato	Shed leaves and straw	No*
Cassava	Shed leaves, small branches, planting stakes	No*
Yam	Shed leaves and dead vines	No*
Banana	Dead leaves and the cut-up trunk	No
Coffee, cocoa	Leaf litter, prunings, pod and cherry husks	No

* Although the fine root system can be left in the soil, this will not be considered as carbon input, unless there are crop-specific data.

7.2 Measurement

Data required for this indicator are: (i) yield and total aboveground dry biomass (kg dry matter/ha), (ii) percentage of crop residues remaining on the field (retained crop residues) after harvesting, and (iii) manure or compost applied (kg dry matter/ha). SOPs for measuring total aboveground biomass are available in the annex for different crops. If no other formula is available, use formula (14) for cereals.

$$\text{Total aboveground dry biomass of crop (kg dry matter/ha)} = \frac{\text{Yield (kg dry matter/ha)}}{\text{Crop-specific harvest index in action sites}} \tag{14}$$

The type and amount of manure or compost, and the percentage of retained aboveground crop residues, can be determined through farmer interviews if organic input is not part of the improved agronomic practices. Since the C concentration of manure or compost is variable, we recommended you use local estimates of C concentration in manure/compost used.

Examples of agronomic gain KPI assessment

This section provides two examples of agronomic gain KPI assessment using data from previous studies (Carrijo *et al.*, 2017; Chivenge *et al.*, 2021; Haefele *et al.*, 2022). These two studies (Carrijo *et al.*, 2017; Chivenge *et al.*, 2021) did not perform on-farm trials but conducted meta-analysis to compare control and improved agronomic practices — site-specific nutrient management (SSNM) practices and alternate wetting and drying (AWD) irrigation — for different KPIs. We consider one observation (or sample) as one farmer's field for data analysis. We do not take into account annual or seasonal factors to assess yield stability. Another study (Haefele *et al.*, 2022) deals with long-term trials for irrigated rice. Here, we will assess yield stability as well as other KPIs.

1. Site-specific nutrient management

SSNM is a dynamic, plant-based, field- and season-specific nutrient management approach that aims to synchronize nutrient supply and demand according to differences in crop requirements, indigenous nutrient supply, and nutrient recovery from fertilizer and other sources. Crops for which specific SSNM solutions have been developed so far include maize, rice, wheat, soybean, cassava and potato. The main objectives of SSNM are to improve crop yield, profit and nutrient-use efficiency. Chivenge *et al.* (2021) performed a meta-analysis comparing SSNM with farmers' fertilizer practice for maize, rice and wheat using 61 published papers across 11 countries. Using data from Chivenge *et al.* (2021), we performed an agronomic gain KPI assessment. Box 1 shows information related to trial design including treatments, sample size and KPIs considered in this study, and other parameters.

The key findings of this assessment are as follows.

- SSNM improved yield by 8–18%, profit by 13–20%, and N- and phosphorus (P)-use efficiencies by 19–29% and 24–23%, respectively, for all three crops (Table 4). Positive agronomic gains in KPIs were observed in 87–98%, 93–

99%, 66–89% and 69–81% of observations in yield, profit, and N- and P-use efficiencies, respectively (Table 4, Fig. 2).
- Potassium (K)-use efficiency had a negative gain, especially for wheat. This is due to the tendency to have a very low K rate in farmer fertilizer management practices, which would not be sustainable.
- There was a significant positive correlation between agronomic gains in yield and profit for all the crops (Figs 3 and 4; data not shown for maize and wheat).
- There was no significant trade-off among agronomic gains in KPIs (Fig. 4).
- Labor productivity, water productivity and C input were not determined in this study. Justification for this decision needs to be reported for a comprehensive assessment of SSNM.

These findings, together with data (including figures and tables) and responses from implementers (for items in the last bullet point), and coupled with the key objective of SSNM, will be used in the decision-making processes on whether to proceed to the next step or not.

Box 1. Description of data used for assessing agronomic gain of site-specific nutrient management (Chivenge *et al.*, 2021)

Treatment:

- Improved agronomic practice: SSNM
- Control: Farmer fertilizer management practice (FFP)

Other practices were the same in the two treatments.

Sample size (here, this is number of trials): 59 (maize), 260 (rice) and 84 (wheat)

KPI:

- Primary product harvested yield (yield, kg/ha)
- N-use efficiency (partial factor productivity for N = PFPN, kg grain/kg N)
- P-use efficiency (partial factor productivity for P = PFPP, kg grain/kg P)
- K-use efficiency (partial factor productivity for K = PFPK, kg grain/kg K)
- Gross return fertilizer or profit (GRF, US$/ha)

KPI related parameter:

- Inorganic fertilizer rate (N, P and K, kg/ha)

Table 4. Average data on KPIs in SSNM and FFP treatments for three crops

Crop	Treatment	Sample size	Yield	GRF	PFPN	PFPP	PFPK	N	P	K
Maize	FFP	59	7,391	949	44	317	230	178	30	48
Maize	SSNM	59	8,373	1,076	53	367	165	161	25	57
Rice	FFP	260	5,605	1,227	47	275	176	132	23	45
Rice	SSNM	260	6,058	1,381	58	315	139	113	23	53
Wheat	FFP	84	4,250	696	28	167	1,294	154	26	16
Wheat	SSNM	84	4,997	837	36	206	101	138	27	53
Maize	Relative agronomic gain (%)	59	13	13	19	16	−28	−10	−18	18
Rice		260	8	13	25	14	−21	−14	0	18
Wheat		84	18	20	29	23	−92	−11	2	228
Maize	% of sample having positive agronomic gain	59	98	98	66	69	45	55*	64*	24*
Rice		260	87	93	77	77	60	70*	49*	30*
Wheat		84	95	99	89	81	27	62*	46*	10*

For abbreviations and units, see Box 1.

* N, P and K reduction are considered as positive agronomic gain.

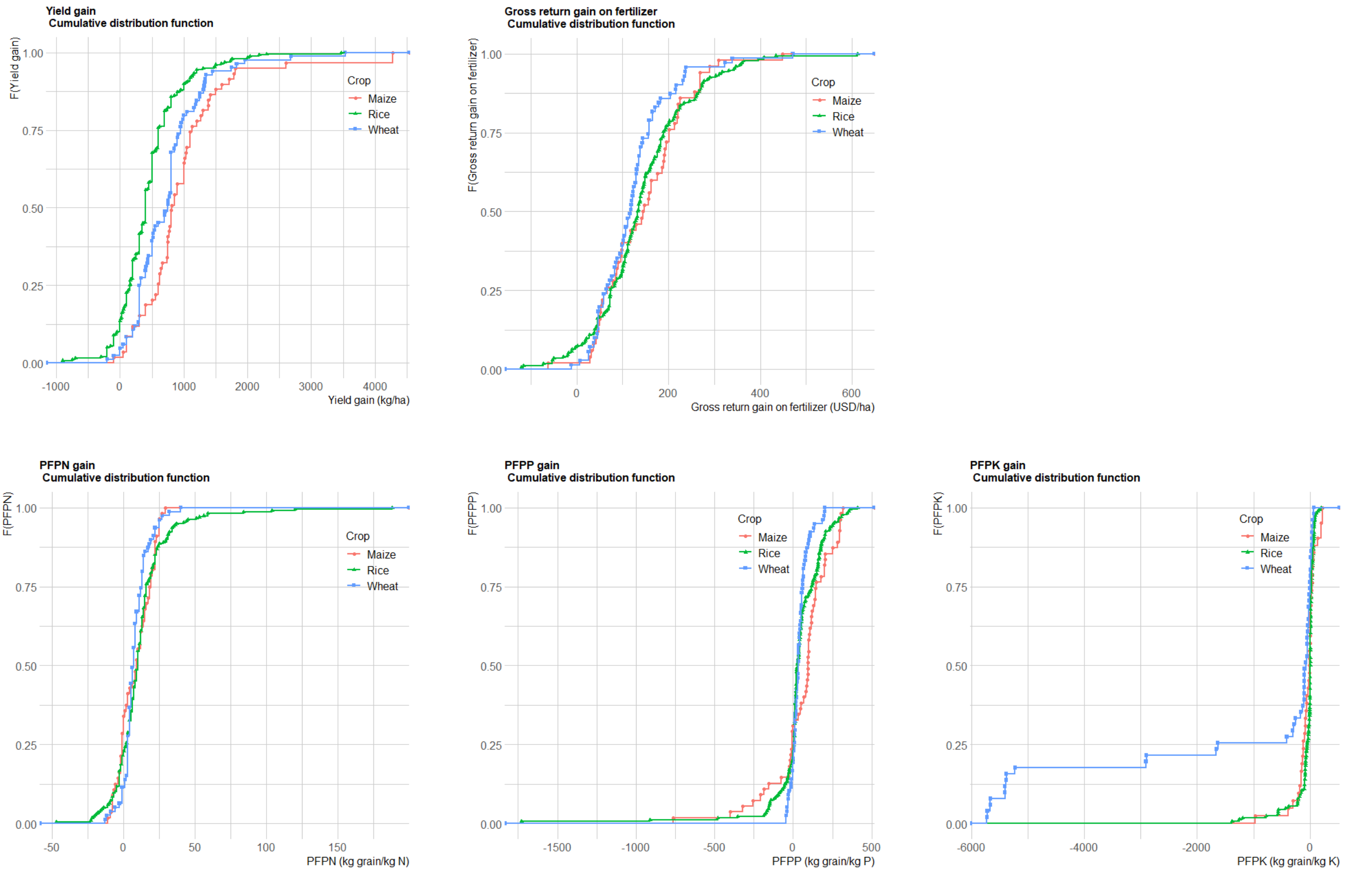

Figure 2. Distribution of agronomic gain in KPIs between SSNM and FFP

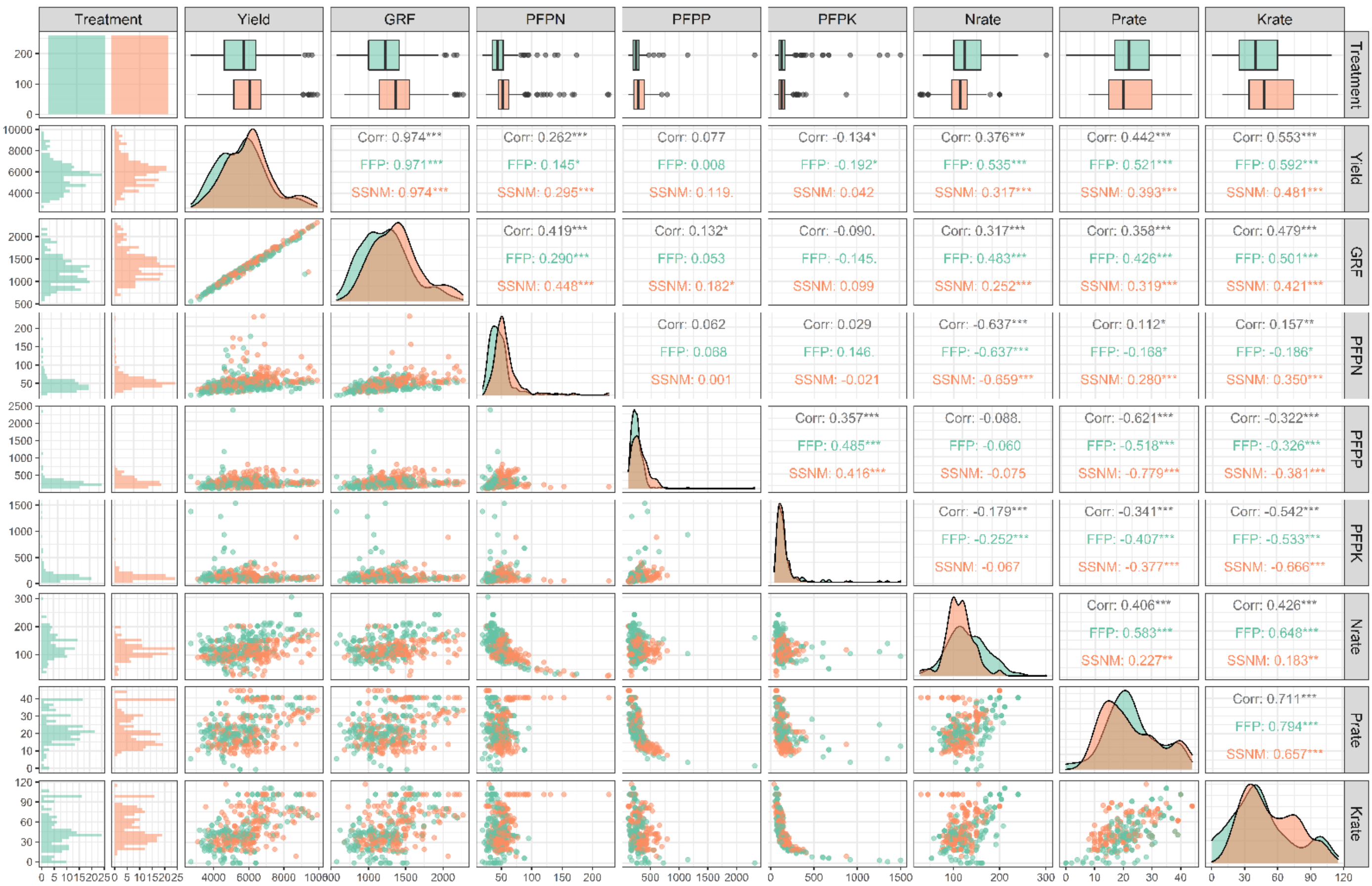

Figure 3. Correlation among KPIs and their related parameters for rice

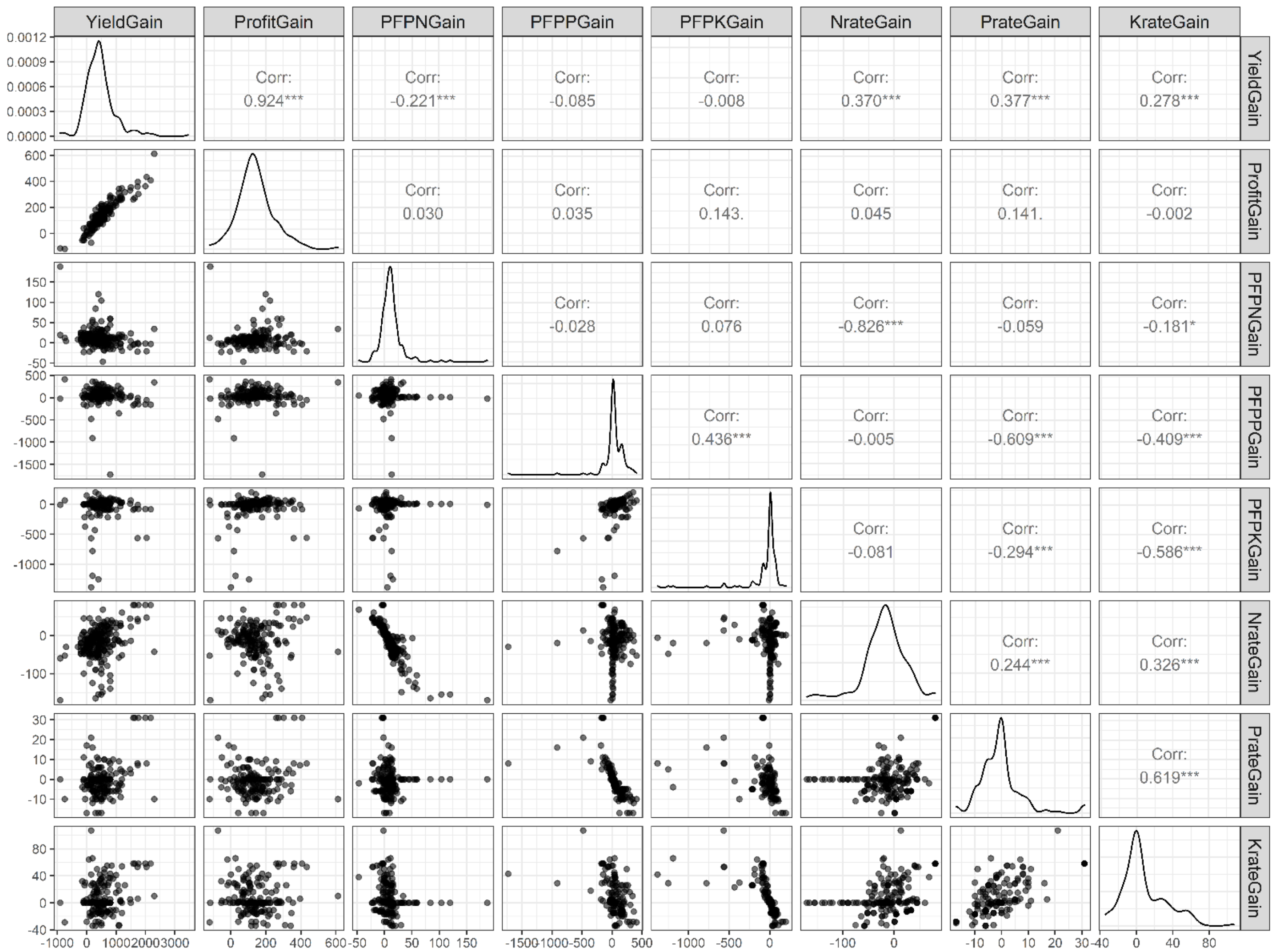

Figure 4. Correlation among agronomic gains in KPIs and their related parameters for rice

2. Alternate wetting and drying irrigation

Irrigated rice systems require more water than other major crops. Alternate wetting and drying (AWD) is an irrigation practice (introduction of unsaturated soil conditions during the growing season) that can reduce water inputs to rice. Some previous studies showed that AWD significantly reduced yields. Carrijo *et al.* (2017) conducted a meta-analysis to quantify the effect of AWD on rice yields and water use by analyzing data from 525 side-by-side comparisons between AWD and continuous flooding. Using data from Carrijo *et al.* (2017), we performed KPI assessment. Box 2 shows information related to trial design including treatment, sample size, KPIs considered in this study and other parameters.

The key findings of this assessment are as follows.

- AWD significantly reduced water input by 21% on average without substantial yield reduction (Table 5). Consequently, AWD improved water productivity by 30% on average.
- A positive agronomic gain in water productivity was observed in 83% of observations, whereas water input was reduced in 98% of observations (Table 5, Fig. 5).
- Negative agronomic gains in yield and NUE were observed in around 70% of observations (Table 5, Fig. 5).
- There was no large difference in NUE between AWD and continuous flooding (Table 5).
- There was no significant trade-off between agronomic gains in yield and water productivity (Fig. 6).
- Labor productivity and carbon balance were not determined in this study. Justification for this decision needs to be reported for a comprehensive assessment of AWD.
- There is a need to identify the reasons for the large yield reduction due to AWD observed in some of the trials, to help in specifying target domains within action sites for the introduction of AWD.

These findings together with data (including figures and tables) and responses from implementers (for the last two bullet points in this case), coupled with the initial objective of AWD, will be used in the decision-making processes on whether to proceed to the next stages (pilot or scaling stages) or not.

Box 2. Description of data used for assessing agronomic gain of AWD irrigation (Carrijo *et al.*, 2017)

Treatment:

- Improved agronomic practice: AWD
- Control: Continuous flooding

Other practices were the same in both treatments.

Sample size (here, this is number of trials): 525 pair-comparison

KPI:

- Primary product harvested yield (yield, kg/ha)
- N-use efficiency* (partial factor productivity for N = PFPN, kg/kg)
- P-use efficiency (partial factor productivity for P = PFPP, kg/kg)
- K-use efficiency (partial factor productivity for K = PFPK, kg/kg)
- Water productivity (WP, kg/m^3)

KPI related parameter:

- Total volume of water use per season (water input, mm)

*The two treatments had the same fertilizer rates.

Table 5. Average data on KPIs in AWD and control treatments

	Yield	PFPN	PFPP	PFPK	WP	Water input
AWD	5,782	49	232	154	0.91	1,000
Continuous flooding	6,211	54	250	165	0.70	1,326
Relative agronomic gain (%)	−1	−8	−7	−5	30	−21
% of sample having positive agronomic gain in AWD	32	26	31	30	83	98*

For abbreviations and units, see Box 2.

*Reduced water input is considered a positive agronomic gain.

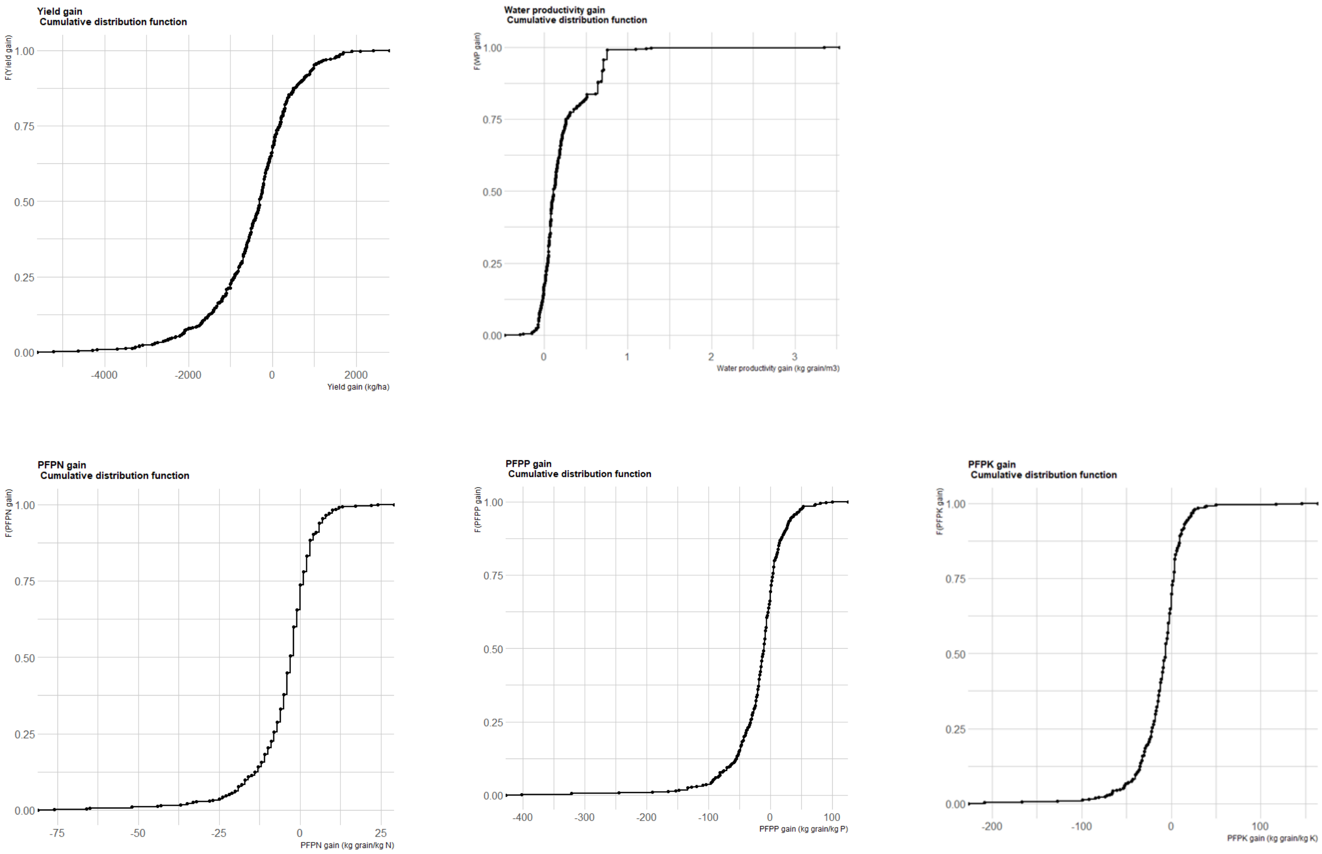

Figure 5. Distribution of agronomic gain in KPIs between AWD and control

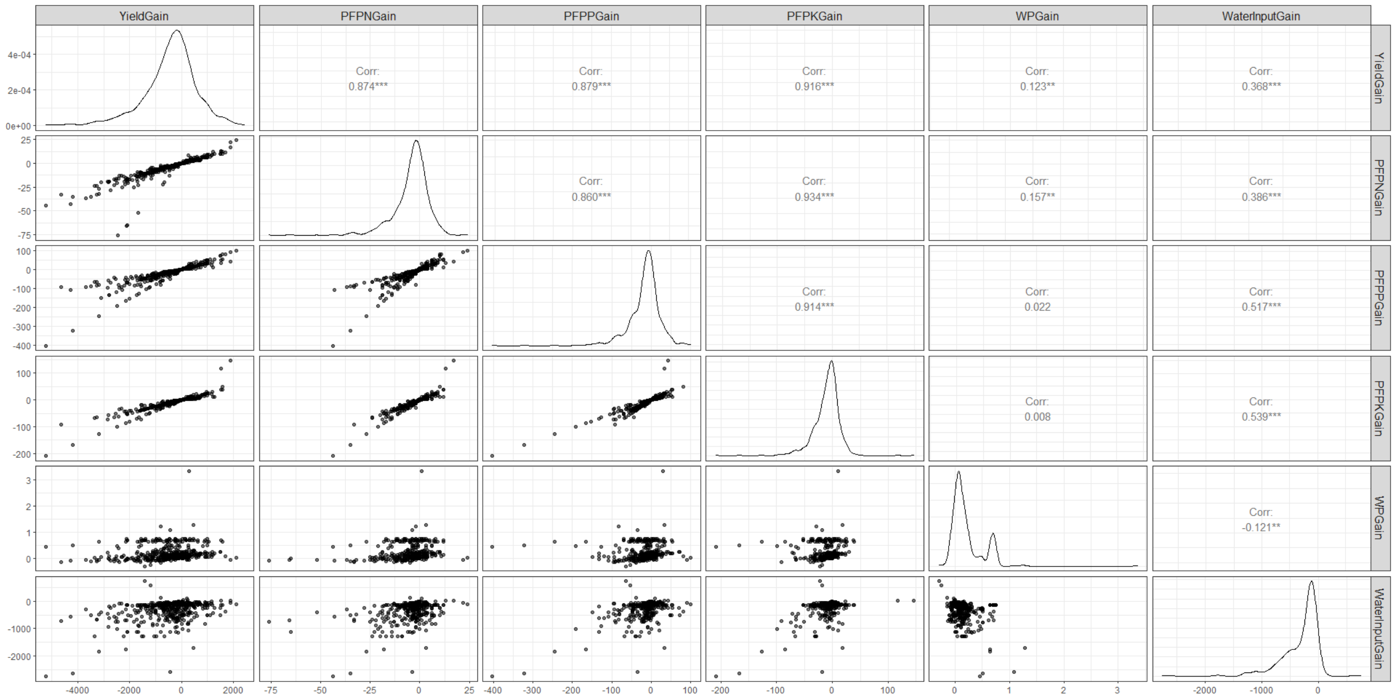

Figure 6. Correlation among agronomic gains in KPIs and their related parameters for rice

3. Long-term fertility experiments for irrigated rice in the West African Sahel

Two long-term experiments were established in 1991 for intensive rice-based irrigated systems in the Senegal River valley at Ndiaye and Fanaye, Senegal (Haefele *et al.*, 2022). The experiments included six fertilizer treatments and rice was grown for two seasons per year.

Using data on three treatments in Fanaye from 1991 to 2007, we performed KPI assessment including yield stability (see Box 3).

The key findings of this assessment are as follows (see Table 6).

- Addition of P and K (over control levels) did not improve rice yield, consequently reducing profit in both seasons. There was no large difference in PFPN and carbon inputs between plots receiving higher PK and controls in both seasons. Sustainable Yield Index (SYI) had inconsistent results across two seasons between the two treatments. Plots receiving higher PK had higher SYI in the wet season, but lower SYI in the dry season (Table .
- Additional N (compared with the control) increased rice yield, profit and carbon input, but reduced N-use efficiency in both seasons. SYI was also increased with additional N in the dry season, which also gave larger agronomic gain in yield.
- There is a trade-off in agronomic gain between plots with additional N and the control. Higher yield gain with additional N was associated with lower N-use efficiency. However, PFPN in additional-N plots was still within optimum range for rice (30–100 kg/kg). There is synergy between increased yield and yield stability, and additional N not only increases yield, but also increases yield stability, especially in the dry season.

Box 3. Description of data used for assessing agronomic gain in long-term fertility experiments for irrigated rice in the West African Sahel (Haefele *et al.*, 2022)

Treatment:

- N-P-K (120–26–50): control
- N-P-K (120–52–100): Higher PK
- N-P-K (180–26–50): Higher N

Four (4) replications per season.

KPIs:

- Primary product harvested yield (yield, kg/ha)
- N-use efficiency (partial factor productivity for N = PFPN, kg grain/kg N)
- Sustainable Yield Index (SYI)
- Carbon input (kg C/ha)
- Profit gain (local currency/ha): difference between control and higher PK, and higher N. Here, fertilizer price, paddy sale price, fertilizer transport cost, fertilizer application cost and harvesting cost were considered.

KPI related parameter:

- Coefficient of variation (CV, %) of yield

Table 6. Average data on KPIs in long-term fertility experiments for irrigated rice in Fanaye, Senegal, West African Sahel (Haefele *et al.*, 2022)

Season	Treatment	Yield (kg/ha)	SYI	CV (%)	PFPN (kg/kg)	Carbon input (kg/ha)	Profit (local currency/ha) (cf. control)
Dry season	N-P-K (120–26–50) (control)	6,191	0.54	22	52	221	–
	N-P-K (120–52–100)	6,344 (153)*	0.49 (–0.05)	23 (1)	53 (1)	227 (6)	(–26,480)
	N-P-K (180–26–50)	7,488 (1,297)	0.61 (0.07)	18 (–4)	42 (–11)	267 (46)	(185,761)
Wet season	N-P-K (120–26–50) (control)	6,733	0.67	17	56	241	–
	N-P-K (120–52–100)	6,905 (172)	0.74 (0.07)	12 (–5)	58 (2)	247 (6)	(–22,952)
	N-P-K (180–26–50)	7,370 (637)	0.68 (0.01)	18 (1)	41 (–15)	262 (21)	(84,147)

cf., compare; CV, coefficient of variation; PFPN, partial factor productivity for nitrogen; SYI, Sustainable Yield Index.
* Absolute difference between improved practices and control.

Frequently asked questions (FAQs)

Q1: Is it really necessary to assess all KPIs in on-farm trials for validating new, improved agronomic practices? If improved agronomic practices focus on nutrient management, labor use/water input would most likely not be changed by the introduction of improved agronomic practices.

In this case, implementers could use the same data on local estimates of water input and labor input in both improved agronomic practices and controls to calculate labor productivity and water productivity. This should be clearly mentioned when implementers report KPIs. If frequency of fertilizer application is significantly increased with introduction of improved nutrient management practice, such increase in labor input should be estimated and taken into account for calculating labor productivity.

Q2: How should agronomic practices be assessed in different R&D steps?

This is beyond the scope of this document. However, by way of a brief introduction to assessment approaches in other stages we offer the following. In the **discovery stage** (see Fig. 1), farmers' agronomic practices and current level of adoption of improved agronomic practices can be assessed through surveys consisting of household interviews and field observations. A data collection tool has been developed by the EiA add-on team.

If field-based measurement is considered, entire field-level evaluation of improved agronomic practices in the **pilot stage** requires a different sampling method from those detailed in this document. For example, crop cut for yield assessment is not feasible at entire field level, but needs to be done in representative plots. Alternatively, interview-based data collection can be considered. Such an approach is used for discovery stage (see above), randomized control trials (RCTs) in pilot stage, and panel study in **scaling** (see Fig. 1).

Q3: Labor input cannot be determined properly using small plots in proof-of-concept stage. How can we deal with this?

If labor input is not expected to change much with the introduction of improved agronomic practices, labor input and labor productivity can be estimated (see Q1). If improved agronomic practices are expected to result in a large change in labor input, a larger plot size should be used in selected fields to quantify labor input. Alternatively, labor productivity can be assessed during the pilot stage when improved agronomic practices could be evaluated at the entire field level.

Q4: In large-scale on-farm evaluation, assessing KPIs for all farmers would not be feasible. How can we deal with this?

We suggest sub-sampling for data collection on some KPIs. For example, if implementors test in 1000 farmers' fields, 10% of fields could be used to determine all KPIs.

Q5: How do we look at trade-offs, once all indicators are agreed upon?

See section on examples of agronomic KPI assessment for SSNM (page 9 and Fig. 4) and AWD (page 12 and Fig. 6) and correlation analysis. You could also use radar charts or parallel coordinates plots to compare different KPIs.

Q6: Detailed measurement of irrigation water input is not easy in on-farm trials. How can we deal with this?

We suggest measuring irrigation water input in at least some of the farmers' fields. Alternatively, establish an empirical relationship between number of irrigations and water input in the action sites. Then, data on number of irrigations can be collected through farm diary records.

Q7: The answer to Q6 mentioned "establish an empirical relationship between number of irrigations and water input". What about other KPIs?

How can we evaluate different approaches for establishment of empirical relationships among KPIs or between agronomic practices and KPIs?

Can we do this with on-farm trials alone? If not, what is needed?

This requires data on farmers' current practices and KPIs in action sites. These will be collected in add-on activities in the discovery stage as well as during the pilot stage (see Q2). These data will be useful to identify linkages between agronomic practices and KPIs and among KPIs.

Q8: How about other important indicators such as yield quality and greenhouse gas emissions?

What will be the KPI for yield quality, especially for crops that are produced for processing?

Other KPIs could be included later. Soil health and agro-fortification groups in EiA are working on this.

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Contributors

Kazuki Saito, Jean-Martial Johnson (Africa Rice Center [AfricaRice]), Stefan Hauser (International Institute of Tropical Agriculture [IITA]), Marc Corbeels (IITA/Centre de coopération internationale en recherche agronomique pour le développement [CIRAD]), Mina Devkota (International Center for Agricultural Research in the Dry Areas [ICARDA]), Madonna Casimero (International Rice Research Institute [IRRI])

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Suggested citation: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. 2022. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*, v. 1. Africa Rice Center, Abidjan, Côte d'Ivoire.

Guideline for measuring agronomic gain key performance indicators (KPIs) in on-farm trials

Annex: Standard operating procedures

001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations

002 Field area measurement

003 Measurement of barley grain yield and aboveground biomass at maturity for crop cut at plot level

004 Measurement of cassava root yield and aboveground biomass by crop cut at plot level

005 Measurement of maize grain yield and aboveground biomass at maturity by crop cut at plot level

006 Measurement of potato tuber yield at maturity by crop cut at plot level

007 Measurement of rice grain yield and aboveground biomass at maturity by crop cut at plot level

008 Measurement of sorghum grain yield and aboveground biomass at maturity by crop cut at plot level

009 Measurement of wheat grain yield and aboveground biomass at maturity for crop cut at plot level

Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations

SOP ID: 001

Version: 1

Crop: All crops

Relevant KPI: Productivity — yield; Resource use efficiency — nutrient use efficiency

R&D stage (example of activities):

- Discovery stage (yield decomposition)
- Proof-of-concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Pilot stage (on-farm participatory trials, randomized control trial)
- Scaling stage (panel studies, ex-post impact assessment)

Background

To correctly express the yield of any crop, it is of paramount importance to correctly determine the surface area from which the crop is harvested. The determination of the minimum harvest area is connected to the plant density and thus the minimum number of plants that would need to be harvested to attain repeatable results. This SOP is separated into three modules to accommodate the wide range of plant densities of the relevant crops. The first module is on crops sown or planted at high density (usually > 20 plants or hills/m^2), such as cereals (rice, wheat, barley), small-seeded pulses and certain oil seeds. The second module is on large cereals such as maize and sorghum and most root and tuber crops such as cassava, sweet potato, potato and yam, which are sown or planted at medium densities ranging from around 1 to 20 plants or hills/m^2. The third module is on perennials such as banana and plantain, and on tree crops such as cocoa and coffee, which are planted at low densities and where individual plants may be assessed rather than whole plant populations.

Recommended equipment

- Pegs
- Tall poles > 2 m high
- Measuring tape
- Ruler of 2 m length
- Fixed sampling frames of metal, wood or plastic (usually up to 1 m^2)
- Rope, strong and not flexible (does not extend when pulled)
- Angle prism
- GPS or smartphone with a field measurement app
- Range finder to measure distances in large fields

General methods and rules for delineating a harvest area

Irrespective of whether crops were sown or planted in a regular or irregular manner, there are a number of methods to establish harvest areas of correct surface area. Unless fixed frames are used, the researchers need to determine which method of delineating harvest areas is most appropriate for their situation and purposes. In addition to the method, there are rules that apply to where the corner points of harvest areas are to be placed, depending on the density of the crop and the seeding or planting pattern.

Delineating correct harvest areas

Squares and rectangles

Most research plots are rectangular or square and thus offer themselves to delineate rectangular or square harvest areas after removing sufficient border area. To delineate a rectangular- or square-shaped harvest area it is of paramount importance to ensure that all angles are exactly 90°. If a square-shaped harvest area is chosen, the verification of the angles can be done by measuring the diagonal according to the rule:

$$a^2 + a^2 = c^2 \text{ or } 2 \times a^2 = c^2 \qquad (1)$$

where a is the length of one side of the square and c the length of the diagonal.

A simplification of the calculation is the multiplication of the side length of a square with the factor 1.414214, which is an approximation of equation (1).

Table 1 gives values for a, $2 \times a^2$ and c in meters for various side lengths of squares. The length of c is rounded to the nearest centimeter.

Table 1. Examples of side length (m) and diagonals (m) of square-shaped harvest areas

a	$2 \times a^2$	c
0.5	0.5	0.71
0.75	1.125	1.06
1	2	1.41
1.25	3.125	1.77
1.5	4.5	2.12
1.75	6.125	2.47
2	8	2.83
2.5	12.5	3.54
3	18	4.24
3.5	24.5	4.95
4	32	5.66
5	50	7.07
6	72	8.49
7	98	9.90
8	128	11.31

If rectangular harvest areas are chosen, the principle of Pythagoras [Equation (2)] applies when calculating the diagonal of any rectangle.

$$a^2 + b^2 = c^2 \qquad (2)$$

where a and b are the side lengths of the rectangle and c is the diagonal.

There are no simplifications as when using squares, but the least difficult is to use a rectangle with the side lengths 3 m and 4 m for a and b, which has a diagonal length of 5 m. Depending on the plot size any multiple of these can be used.

Triangles

Equilateral triangles are the only shape that will, without verification of the angles, give the exact shape and surface area if all sides are of the same length (equilateral) and all sides are straight. Equilateral triangles are a convenient way to delineate harvest areas in irregularly sown or planted crops but can be used in regularly sown or planted crops as well.

The area inside an equilateral triangle can be calculated with equation (3).

$$A = a^2 \times 0.433 \qquad (3)$$

where A is the area inside the triangle and a is the side length of the triangle. Table 2 shows some examples of side lengths and areas of equilateral triangles.

Table 2. Examples of side length of and area within equilateral triangles

Side length (m)	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Area (m^2)	2.71	3.90	5.30	6.93	8.77	10.83	13.10	15.59

Side length (m)	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
Area (m^2)	18.29	21.22	24.36	27.71	31.29	35.07	39.08	43.30

Circles

In situations with very sparse and low-growing vegetation it can be appropriate to mark circles and harvest within them. However, this approach requires that the person making the circle can move unimpeded and the marker is not obstructed by crops.

To delineate a circle, a center pole or pin is required that is firmly pushed into the ground and does not move. A string or rope, that does not extend when pulled, is tied to the center pole and at the required radius length a second peg is tied. Then the rope is stretched straight and with one tip in the soil to mark the circle the second peg is moved around the center pole. The peg used for marking needs to be held in a vertical position throughout the marking process. This is easiest when the rope is attached close to the bottom end of the marker peg.

The surface area inside the circle is calculated by equation (4).

$$A = r^2 \times \pi \qquad (4)$$

Where A is the surface area, r the radius of the circle and π the constant pi here used as 3.14159. Table 3 shows in the first two lines the surface area at fixed radii and in the following two lines the required radii to attain fixed specific areas.

Table 3. Examples of radii (r) in meters and surface areas (A) (m^2) of circles

r	0.25	0.5	0.75	1	1.25	1.5	2	2.5	3	4
A	0.196	0.785	1.767	3.142	4.909	7.069	12.566	19.635	28.274	50.265

A	1.003	2.011	3.017	4.011	5.003	6.000	10.066	15.067	20.030	29.996
r	0.565	0.8	0.98	1.13	1.262	1.382	1.79	2.19	2.525	3.09

Exceptions

In tall and dense stands of cassava, maize or sorghum, or any other tall crop, and specifically when the crop is lodging, the *a priori* delineation of a harvest area with ropes may not be feasible as it may not be possible to establish straight lines without causing major damage to the plants.

Here a different approach needs to be taken.

From a selected spot in the field the crops are harvested along an imaginary straight line (baseline in blue in Fig. 1) until the required side length of the intended harvest area is reached. Pegs ⊗ are driven into the soil at the beginning and the end of the line and the direction into the harvest plot at approximately 90° angle is indicated with a long pole placed on the ground (brown arrows in Fig. 1) at each end of the baseline. Then the harvest continues between the two poles until sufficient area or a sufficient number of plants is harvested. After the harvest the side lengths of the plot need to be measured to verify the harvest area and the correct angles. If a harvest area is not square or rectangular but rhomboid, the two diagonals need to be measured (red lines in Fig. 1) and recorded, best by making a sketch as shown in Figure 1.

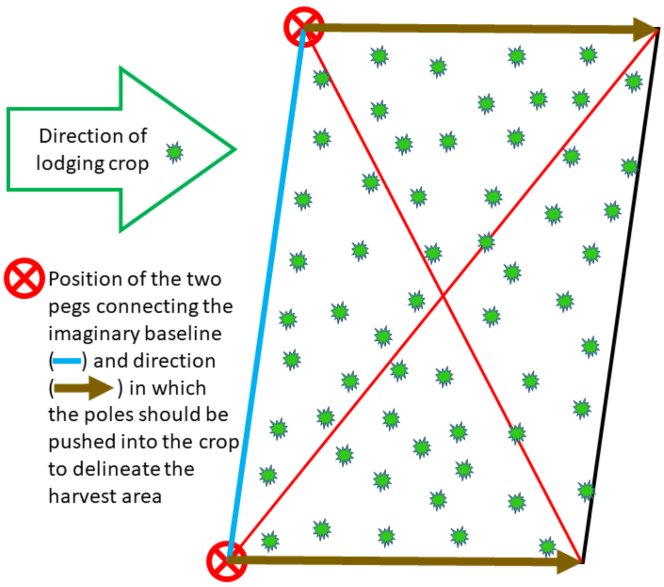


Figure 1. Examples of harvest areas with a deviation from right angles

As it is not possible to measure the actual angles in the field, the area can be calculated with the help of the diagonals and sectioning the harvest area into several triangles each with one right angle.

If a harvest is conducted on a larger area or an entire field and the area is not a square or rectangle, it is advised to walk the outer boundary of the harvested area with a GPS of sufficient resolution and use the GPS area function to obtain the surface area. Mark your start point with a well visible pole so you return to exactly the same point. While walking the outer boundary it is necessary to move the GPS exactly over the border of the field, not inside or outside. Note that the GPS may be held away from the body and pass in a different place from where the person is walking thus introducing error. However, not all GPSs have an area function and in many places GPS signals may not provide for a high enough resolution to get an exact area estimate. The person in charge needs to assess whether the GPS readings are good enough or whether geometric methods need to be used to correctly determine the harvest area. Please refer to the SOP 'Field area measurement by GPS' for recommended GPS brands and smartphone applications.

Rules on delineating the correct size of the harvest areas

High-density crops sown in rows

In regularly sown or planted crops the harvest area needs to be compatible with the planting pattern and the delineation needs to consider the distances between rows or between stands (such as when planted on mounds) or individual plants. Generally, the placement of the harvest area must consider the spatial arrangement of the plants.

In high-density crops, sown or planted in rows, yet with irregular distances within the row or (as in many rainfed cereals) in rows that are not a single line of plants but a broad band of plants, the length across the rows of the harvest area must be a multiple of the row distance. As an example: if the row distance is 0.15 m, the width of the harvest area must be 0.6, 0.9, 1.5 or 2.25 m or any multiple of the row distance across the rows. The width of the harvest area cannot be 1.00 m, 2.00 m or any other length that does not divide by 0.15.

It is important to respect the fact that the border plants are exposed to conditions different from those in the center of the plot, especially if there are bare paths between plots. For this reason, the harvested area needs to be surrounded by plants of the same treatment. In cereals with close row distances (< 0.25 m) there should be at least two rows to either side of the net plot as a border and at least double the row distance at the start and the end of the harvested row length (Fig. 2). At larger row distances (> 0.25 m), a single row and single-row distance at the start and end should be used as borders.

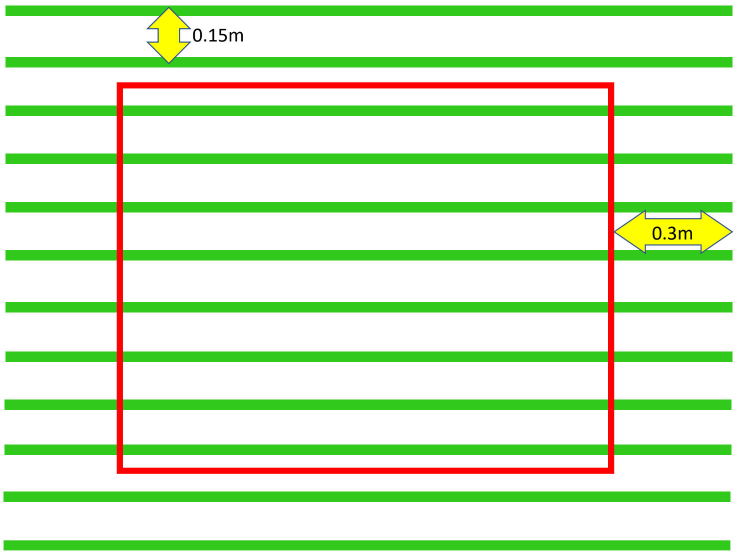


Figure 2. Example of a plot sown at 0.15 m row distance

Two rows on each side are borders and at least 0.3 m is allowed as a border at the start and end of the rows. The red rectangle delineates the maximum area of the plot that can be used to determine the yield.
Not to scale.

Medium-density crops in regular patterns

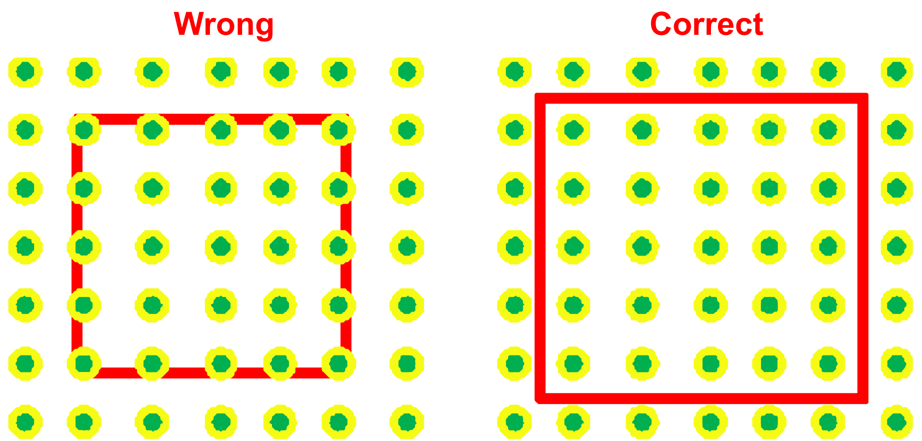
Similar to the situation in row-sown high-density crops, it is necessary to adjust the size and placement of the harvest area in medium-density crops to their planting patterns. However, there appears to be a misconception of where, within a plot, the boundaries between plants run. It can sometimes be observed that harvest plots are pegged from plant to plant, ignoring the fact that plants should never be growing on boundaries. This leads to a major error of having plants on two or all boundaries harvested. The error introduced by such practice is significant because more plants will be harvested from the sampling area resulting in artificially inflated yields. Ideally, sub-plot boundaries (the boundaries of the harvest area) should generally run in the middle between plants in both directions (Fig. 3).

You need to bear in mind that in plots that were manually or mechanically ridged or mounded the distances between ridges or mounts (thus plants) are often not exactly as predetermined due to the relative inaccuracy of the tillage operations. Here specifically, a correction of the area may be required by verifying the total side lengths and widths of the harvest area on all four sides.

Low-density crops in regular patterns

In low-density crops, such as banana and plantain, or tree crops, such as coffee, cocoa, cashew and oil palm, the same rules to place a harvest area apply as in medium-density crops. The distances between individual plants are larger and so are the harvest areas, yet the rule of boundaries running exactly in the middle between plants still applies.

There is one exception, which is for crops planted in a triangular pattern (Fig. 4). Here the shortest distance between neighboring plants forms an equilateral triangle and not a square or rectangle. Therefore, it is not possible to delineate a square or rectangular shaped harvest area and to retain the boundaries exactly in the middle between



A crop planted at 1 m by 1 m distance. Borders drawn along the planting row and comprising 5 × 5 = 25 plants, yet considering a distance from the first to the last plant of 4 m. Thus, calculating the yield from 25 plants on 16 m^2. This is using only 64% of the area actually allocated and thus overestimates yield by 46%.

At the same planting density, the correct border runs in the middle between plants (rows) and will be measured at the 5 m × 5 m that is actually occupied by 25 plants.

Figure 3. Correct setting of the borders between plants to obtain correct areas allocated to plants in a sub-plot to be harvested

plants. The easiest option in such cases is to determine the number of plants to be harvested and to multiply by the area allocated to each plant.

The area allocated to each plant is equal to twice the area of the triangle formed between three neighboring plants and calculated by equation (5).

$$A = 2 \times (a^2 \times 0.433) \tag{5}$$

Where A is the surface area allocated to each plant and a is the distance between two neighboring plants.

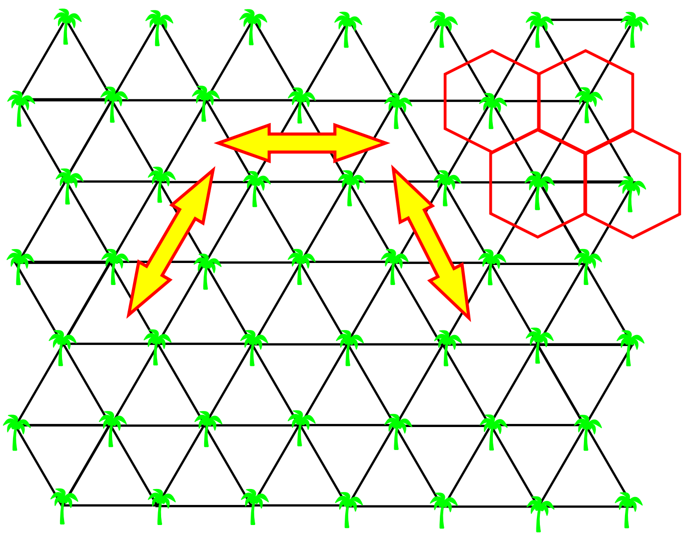


Figure 4. Example of the plant arrangement of a tree crop planted in a triangular pattern

Plant rows are visible in three directions. Each plant is allocated a hexagonal area (red lines).

Crops sown or planted in irregular patterns

Irrespectively of the plant density, crops sown or planted in irregular patterns or broadcast do not require specific rules on where in a plot to place the harvest area, except that you must respect the minimum size of the borders. Depending on plot size and shape the maximum feasible area, after border removal, should be delineated for the harvest.

Although unusual, if relatively small research plots were sown by broadcasting, the area inside the plot to be harvested needs to be delineated with sufficient borders. As a rule of thumb, for high-density crops, the net harvest area should be delineated by moving from each corner of the plot by 0.25 m. As an example: in a plot of 2 m length × 2 m width, the net plot would measure 1.5 m × 1.5 m = 2.25 m^2, because from the length and width of 2 m the distance of 2 × 0.25 m is removed.

In medium-density crops, the border should be at least 0.5 m on all sides; however, it should be adjusted to reflect approximately the average distance between plants in the plot. Example: a plot of cassava, measuring 8 × 8 m gross, contains 64 plants, which is 1 plant/m^2 and would be achieved in regular plantings by a pattern of 1 m × 1 m. Here a border of 1 m would be appropriate, thus the net harvest area should be 6 × 6 m.

To approximate the appropriate border size the following calculations should be used.

$$\text{Plant density (m}^{-2}\text{)} = \frac{\text{Number of plants in a plot}}{\text{Plot surface area (m}^2\text{)}} \tag{6}$$

and

$$\text{Distance between plants (m)} = \frac{1}{\sqrt{(\text{Plant density [m}^{-2}\text{]})}} \tag{7}$$

Example: a maize plot of 5 × 4 m contains 76 maize plants.

Thus, plant density = 76 / 20 m^2 = 3.8 plants/m^2.

$\sqrt{3.8}$ = 1.949 and 1 / 1.949 = 0.513, thus close to 0.5 m – Here a border of 0.5 m width would be appropriate.

In low-density crops, equations (6) and (7) should be used to estimate the border widths.

Generally, the harvested area in research plots should be as large as possible after removal of borders. It is not acceptable to reduce the harvested area by increasing the border size beyond the required dimensions or delineating a small area within a large plot.

Recommended minimum harvest areas and number of plants

High-density crops

Cereals, small pluses and some oil crops are usually sown or planted at high density (usually > 20 plants or hills/m^2). Whether sown mechanically, in rows, planted irregularly or broadcast, a defined area needs to be delineated to be harvested. Although plant or tiller density may be important in these crops, the yield determination is based on the harvest area only (Table 4) and no minimum numbers of plants are proposed.

Table 4. Recommended harvest areas (m^2) for high-density crops

Crop	Research plots[1]		On-farm plots		Notes
	Regular	Irregular	Regular	Irregular	
Rice[2]	4.0	5.0	4.0*	5.0*	* needs to be repeated within the plot.
Wheat	4.0	6.0	4.0*	8.0*	
Barley	4.0	6.0	4.0*	8.0*	
Teff	4.0	4.0	4.0*	4.0*	

[1] Regular = regularly spaced; Irregular = irregularly spaced. [2] According to IRRI (2015).
* See section 'Yield estimations on farm' (below).

Medium-density crops

Root and tuber crops (cassava, sweet potato, yam), large cereals (maize and sorghum) and some pulses are often sown or planted at row distances wider than in small-grained cereals and there are clearly discernible distances within the row. Plant densities are medium, ranging from less than 1/m^2 to 20/m^2. The actual plant densities within a crop vary widely due to differences between agro-ecological regions, cropping systems and varieties. Therefore, depending on the actual plant density, the area to be harvested can be highly variable. As an example, cassava may be planted at densities ranging from 0.5 to 2 plants/m^2 — four times the area would need to be harvested to harvest the same number of plants at 0.5/m^2 density than at a density of 2/m^2. For this reason, it is more important to adhere to the minimum recommended number of plants to be harvested rather than to any recommended area. The recommended minimum harvest areas and the minimum numbers of plants to be harvested are shown in Table 5.

Table 5. Recommended harvest areas (m^2) and minimum numbers of plants to be harvested for medium-density crops

Crop	Harvest area in square meters[1]				Minimum no. plants to be harvested	
	Research plots		On-farm plots		Research plots	On-farm plots
	Regular	Irregular	Regular	Irregular		
Cassava	12	20	20	32	12	24
Potato	10	15	15	25	35	50
Yam	16	32	24	40	12	24
Maize	6	12	10	15	30	45
Sorghum	6	12	10	15	30	45

[1] Regular = regularly spaced; Irregular = irregularly spaced.

Low-density crops

In regularly planted low-density crops such as banana and plantain it is often perceived that — due to the large distances between plants, which can be up to 4 m (in at least one direction) — there is no need to consider border plants. Unfortunately, there is no verifiable information on border effects at planting distances as large as 2 to 4 m. Thus, in research plots it is usual to harvest all plants in a plot and *not* exclude border plants. The reason is that such borders would be highly space consuming. Example: a plantain trial planted at 2.5 m × 2.5 m and 25 plants per plot is 156.25 m^2. If this plot had one row of plants as border it would require 306.25 m^2 — almost twice as large, if the plot is square shaped, which is the most space efficient shape.

In tree crops, the situation is similar, yet distance between trees might be even larger and thus space for borders would be larger as well.

In on-farm tree crop fields it is common to delineate plots to comprise the required minimum number of trees and to leave several trees unused (as a border) before another plot is delineated.

Recommended minimum numbers of plants for low-density crops are given in Table 6.

Yield estimations on farm

High-density crops, irregularly sown

In on-farm situations, the in-field variability must be considered, which cannot always be tackled by enlarging the harvested area (too labor intensive) but needs to be considered by selecting the most representative portions of the crop and harvesting in several positions in case the field displays variability over large portions of the whole area. An assessment of the level of variability and the relative area covered by the different crop situations needs to be done by an experienced agronomist and a sampling scheme implemented to capture the variability across the area.

Table 6. Recommended minimum number of plants to be harvested for low-density crops

Crop	Minimum number of plants to be harvested			
	Research plots		On-farm plots	
	Regular	Irregular	Regular	Irregular
Banana	25	30	30	30
Plantain	25	30	30	30
Cocoa	16	20	25	25
Coffee	15	20	25	30
Oil palm	15	20	25	30

Figure 5 shows an example of a field with variable crop growth, expressed in color: the more green the better the crop; the more yellow the less well developed the crop. In such a field, you need to evaluate which proportion of the field area is covered with a good green (well-developed crop) and how many different levels of crop growth (here green versus yellow areas) can be differentiated. In most fields there will be transition areas that are neither part of the well-developed crop (green) nor of the poorer crop (yellow) but simply in between the two.

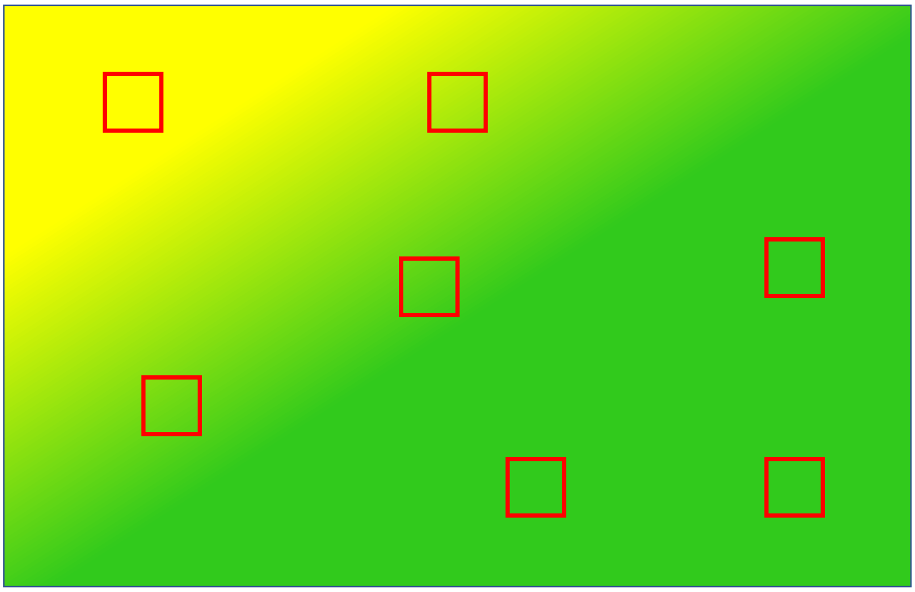


Figure 5. Example of a field with a gradient in crop performance from very good (green) transitioning into a poorer growth portion (yellow)

Red squares are sampling frames.

To correctly sample in such a field, the number of sampling areas needs to be adjusted to the number of situations in the field and their respective areas. In this example, the largest part of the field is well developed, about a quarter is poor and there is a broad band of transition. The red squares would be sampling locations reflecting that most of the field is well developed, with three frames, followed by the transition band with three frames, yet each of the three being of a different greenness to reflect the fact that there is a gradient. Finally, one frame is in the poorer growth area.

The process of sampling frame allocation can be formalized by dividing the field into sections of the same size. Figure 6 shows the same field divided into eight sections and with one sample frame in the center of each. This procedure should produce a number of 'sub-plots', in which the crop performance should be relatively homogeneous. If a field shows strong and abrupt changes in crop performance and has several directions of the gradient, then the field needs to be divided into more sections to attain relatively low heterogeneity within each sub-plot.

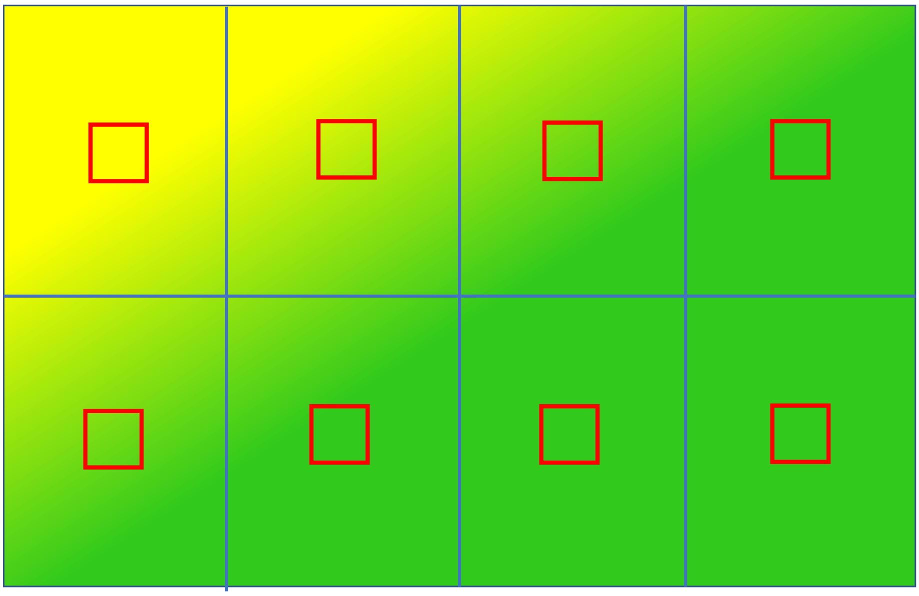


Figure 6. Example of a field with a gradient in crop performance sectioned into eight equal sized sub-plots and one sampling frame in each section

This procedure is more complex if the field is oddly shaped. In this case, the size and shape of the field should be determined with a GPS and mapped. On the map, sampling can be done along parallel lines at fixed distances along each line. Figure 7 shows an example with a gradient in two directions and a sampling approach that takes into consideration the gradient and the area of the different crop performances. The disadvantage of this approach is that more sampling frames need to be harvested, yet for the sake of an appropriate level of precision and accuracy this will be required in on-farm situations.

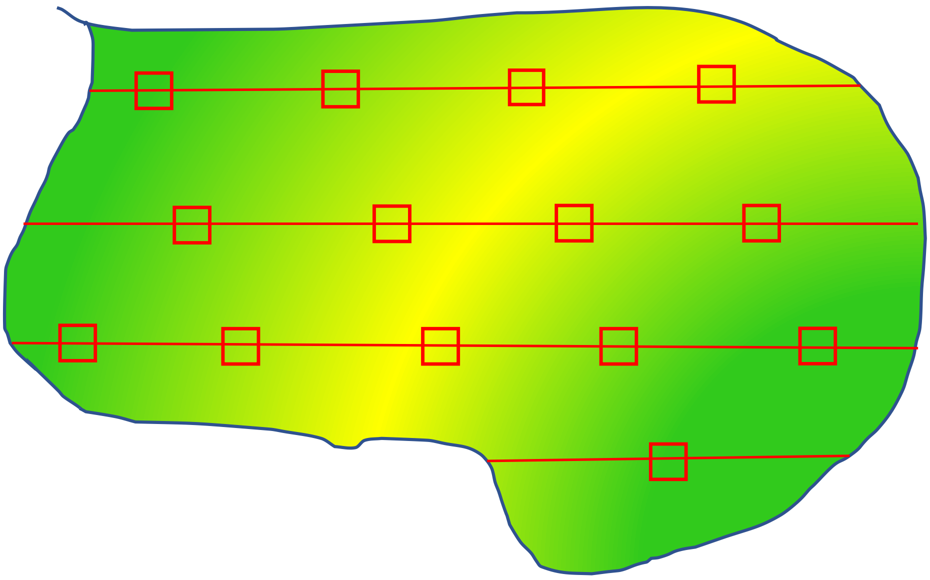


Figure 7. Example of an irregularly shaped field with a gradient of crop performance in two directions

Red lines are transects along which to place sampling frames (red squares) at constant distances to sample the whole field.

Reference

IRRI. 2015. *Standard evaluation system (SES) for rice*, 5th edition. International Rice Research Institute, Manila. www.clrri.org/ver2/uploads/SES_5th_edition.pdf

Contributors

Stefan Hauser (International Institute of Tropical Agriculture [IITA]), Saito Kazuki (Africa Rice Center [AfricaRice])

Suggested citation: Hauser S and Saito K. 2022. Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations, v1. Standard Operating Procedure 001. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d'Ivoire.

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Field area measurement

SOP ID: 00

Version: 1

Crop: Not applicable

Relevant KPI: Productivity — yield; Resource use efficiency — nutrient use efficiency, water productivity and labor productivity

R&D stage (example of activities):

- Discovery stage (yield decomposition)
- Pilot stage (on-farm participatory trials, randomized control trial)
- Scaling stage (panel studies, ex-post impact assessment)

Module description

Accurate measurement of crop cultivated area is essential for assessing various agronomic key performance indicators (KPIs) including yield, profitability and resource use efficiency. Previous household surveys relied heavily on farmer-reported plot areas. However, it has been frequently noted that farmer-reported plot area is often inaccurate for various reasons. Here, we describe the procedure for a global positioning system (GPS)-based field area measurement. Module 1 introduces the use of GPS devices as a first option, and Module 2 describes the use of application software on smartphones and tablets as a second option. We describe UTM [Universal Transverse Mercator] Area Measure, an Android application downloadable free from Google Play Store, as an example. The module describes the procedures for downloading and performing the measurements using this app. There are many other apps with functions similar to those of UTM Area Measure that can also be used to measure field/plot area.

Module 1: GPS-based field area measurement

A GPS uses satellite data to determine a geographic position on the Earth's surface based on longitude and latitude. The position is found by continuous measurement of the time a satellite signal takes to reach your GPS from a satellite in space. The GPS can calculate the geographic position with sufficient accuracy when there are clear signals from at least four satellites. The better a GPS is exposed to the open sky, the more and the clearer signals are received. Please note that, while using GPS in the field, stay away from the shadows of buildings and even large trees.

1.1 Required equipment/materials

- GARMIN GPSMAP or GARMIN OREGON. Once you obtain a GPS device, go through its manual to learn the procedure. Here, we briefly introduce general procedure only.

1.2 Procedure

Step 1: Go to one corner of the field that will be measured.

Step 2: Mark your starting point with a range pole, so that you can identify the exact point when you return. The starting point should be the northwest corner of the field.

Step 3: Turn on the GPS device by holding the power button until an image appears on the screen. The GPS will then seek to acquire satellite signals. Wait until at least four signals appear. Desired margin of error is 2–3 m.

Step 4: Go to the main menu. Select **“Area Calculation”** and press **“Start”**.

Step 5: Walk slowly clockwise around the perimeter of the field. You should hold the GPS flat in your hand and stretch your hand slightly forward. Walk on the edge of the field (not a meter outside or inside the plot). At every corner, you must stop for 5 seconds (counting slowly 1, 2, 3, 4, 5) and then continue walking. You must walk all the way around the field until you return to the location of the range pole (the starting point). Make sure that the correct field boundaries are being measured.

Step 6: When you reach the range pole, click on “**Calculate**”. The GPS will display the area in square meters. You should then record the results to two decimal places. You can change the units according to need.

Step 7: Save the results by selecting “**Save Track”**. Delete the default track name and replace it with your specific field ID. Then, press “**Done”**.

Step 8: To review the track, return to the main menu and navigate to "**Track Manager"**. Use "**thumb stick**" to select the track you would like to review.

Step 9: When you finish, turn off the GPS device by pressing the power button.

Module 2: Use of application software for field area measurement

2.1 Required equipment/materials

- Android-based device (e.g. smartphone or tablet)

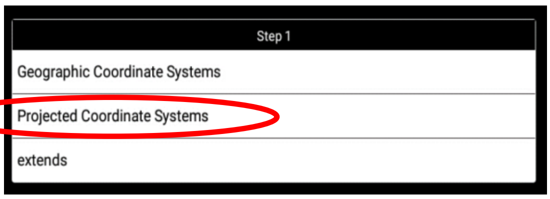
2.2 Procedure for downloading and installing UTM Area Measure app

Step 1: Search for UTM Area Measure in Google Play Store and install it on your device.

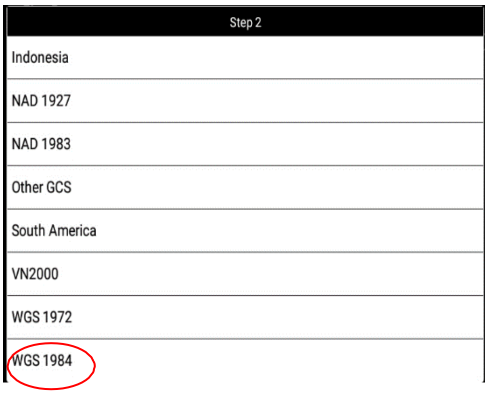
Step 2: Open the app and allow it to access your device's location.

Step 3: To set up a coordinates reference system, press "**Reference settings**".

Step 4: Select "**Projected Coordinate Systems**".

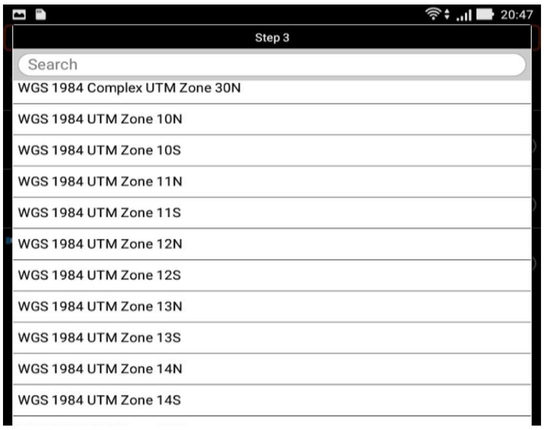


Step 5: Setting UTM Projection, select "**WGS 1984**", which is the standard reference coordinate system for GPS.



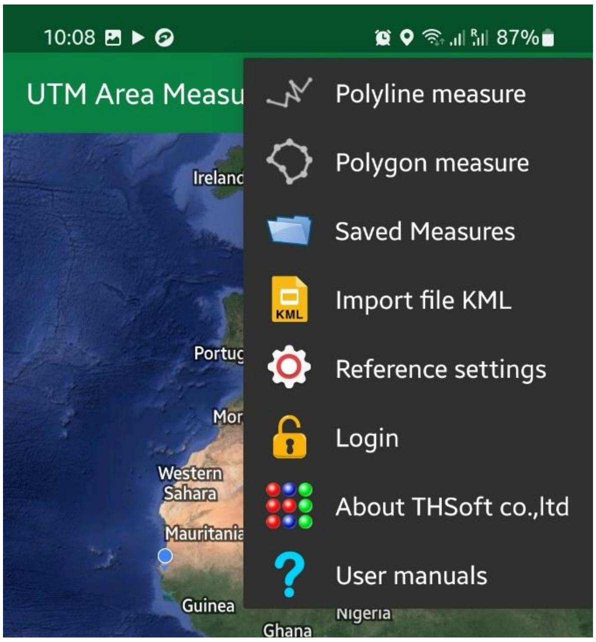
Step 6: Setting UTM Projection, select your zone.

If you do not know the UTM zone of your country, search it online by typing Locality, Country name and UTM zone — e.g. “Kano, Nigeria”, “UTM zone”.



Step 7: When “Reference Settings” is complete, press **OK** to start.

Step 8: Click on “**Menu**” to discover the different utilities.



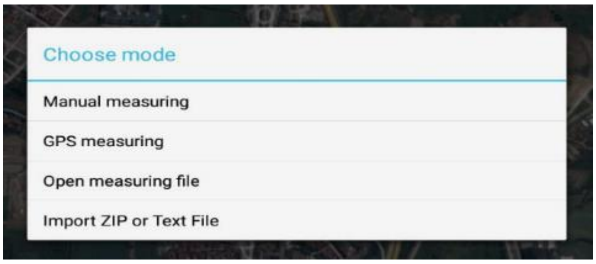
2.3 Measurement procedure

Step 1: Go to one corner of the field that will be measured.

Step 2: Mark your starting point with a range pole so you can identify the point when you return.

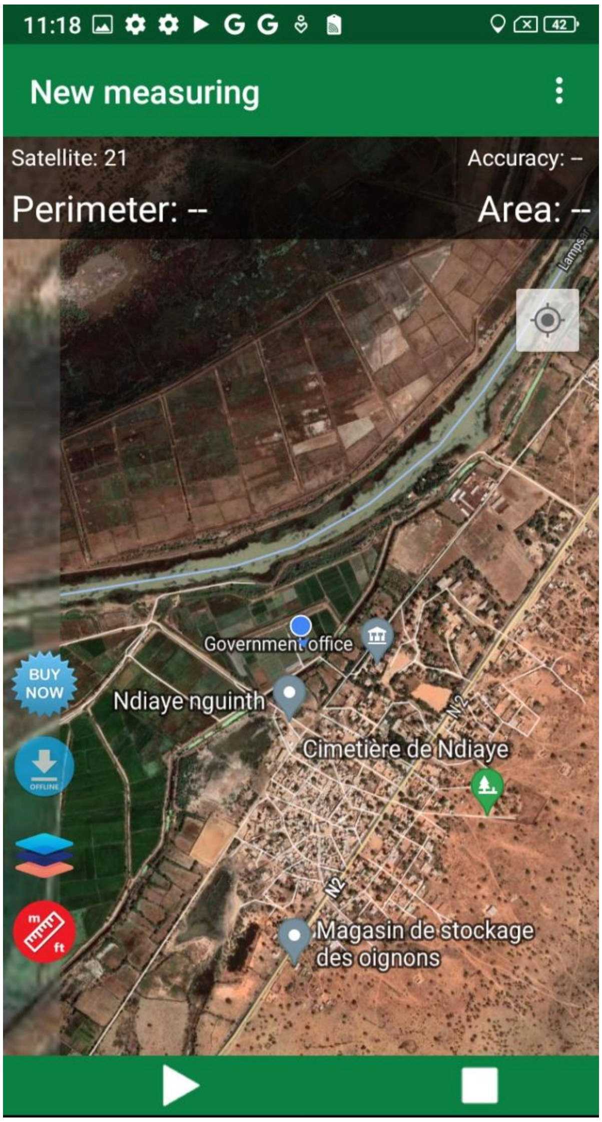
Step 3: Click on **"Menu"**. Then, select "**Polygon measure**". Then, you can see the following measurement modes:

- "Manual measuring": pinning the point on the map by touching.
- "GPS measuring": automatically measure when you move (turn on your location service).
- "Open measuring file": continuing measure from existing file.
- "Import ZIP or Text File": continuing measure from another file format.

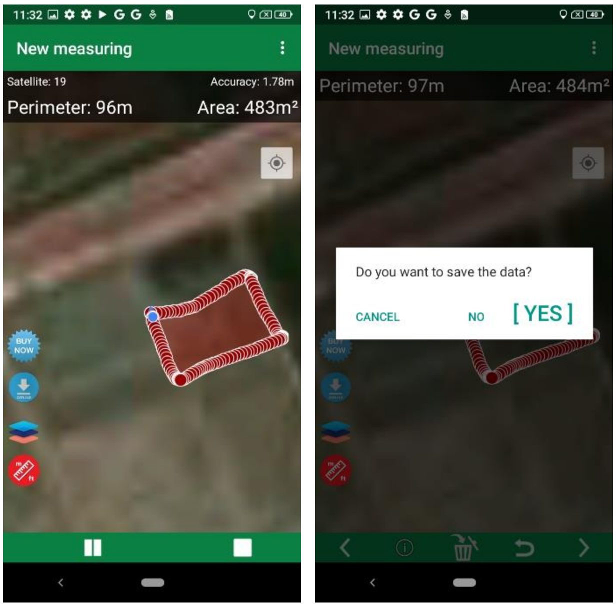


Select one of them.

Step 4: Press "**Start"**, then walk around the perimeter of the field. You must walk on the edge of the field (not a meter outside or inside the plot). At every corner, you must stop for 5 seconds (counting slowly 1, 2, 3, 4, 5) and then continue walking. You must walk all the way around the field until you return to the location of the range pole.

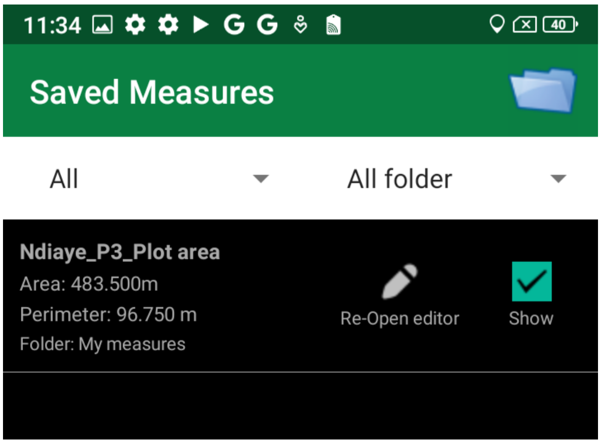


Step 5: After measurement is complete, click on “menu”. Then, press “**Save**”. Then enter the name of the field/plot measurement and the folder name where data will be saved, and press the “Save” icon.



Step 6: To manage saved data, from the menu, select **“Saved measures”**.

Step 7: To show the field/plot sketch, you must click on the name given to the field measurement file.



Contributor

Ali Ibrahim (Africa Rice Center [AfricaRice])

Suggested citation: Ali I. 2022. Field area measurement, v1. Standard Operating Procedure 002. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d’Ivoire.

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Measurement of barley grain yield and aboveground biomass at maturity for crop cut at plot level

SOP ID: 003

Version: 1

Crop: Barley (*Hordeum vulgare*)

Relevant KPI: Productivity — yield; Resource use efficiency — nutrient use efficiency

R&D stage (example of activities):

- Discovery stage (yield decomposition)
- Proof-of-concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Pilot stage (on-farm participatory trials, randomized control trial)
- Scaling stage (panel studies, ex-post impact assessment)

Module 1: Measurement of grain yield

1.1 Required equipment/materials

- Measuring tape
- Four pegs (optional)
- String or rope
- Cloth or woven polyethylene sacks
- Sickle
- Labels
- Marker
- Digital weighing balance
- Grain moisture meter
- Data recording tools/sheet
- Plot combine harvester (optional)

1.2 Procedure for taking sample from field

Step 1: Identify right harvest time: barley is considered ready to harvest when grain moisture content is around 15% or spikes begin to gradually nod downward.

Step 2: Determine net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

Figure 1 illustrates barley seeded in line and random geometry, with the area for net harvesting marked in each. Only the plants that fall *inside* the marked area (inside the red box) need to be harvested. The sampling (net harvested) area is measured and marked out in the field accordingly.

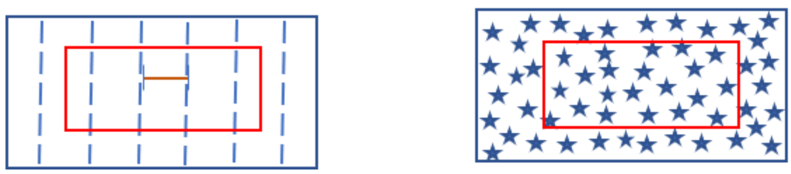


Figure 1. Sampling areas (red rectangles) for barley planted in rows (left) and random geometry (right)

For manual harvesting

Step 3: Locate and mark out the net harvest area by placing four pegs — one at each corner. The dimensions of the harvest area should be representative for the field. When marking net harvest area, take into account crop establishment method. For example, if line seeded, pegs should be placed centrally between rows on both sides (see Fig. 1 left). If plants are in random geometry (e.g. randomly broadcasted), only spikes from stems that fall inside the delineated area should be harvested.

Step 4: Record net harvest area (m^2): width (m) and length (m) as explained in SOP001 (see Step 1).

Step 5: Cut all spikes within the net harvest area and place them in sacks with proper labels (barcode, or full details of location, harvesting date, treatment, replication, plot number, etc.).

Step 6: Transport the harvested spikes to the research station or any other place where samples can be properly processed, dried and stored before measuring grain weight.

Step 7: Thresh spikes manually or mechanically to separate grains from spikes, and clean the grain to remove chaff (i.e. winnow).

Step 8: Measure grain weight (g) from net harvest area using a digital balance and immediately measure the grain moisture content using a grain moisture meter.* Make sure that the balance is placed on a well-leveled surface. Also, make sure the grain moisture meter is calibrated for barley.

When using a plot combine harvester

Step 3: After determining and marking out the net harvest area (in step 2), remove the surrounding border area manually.

Step 4: Record width (m) and length (m) of net harvest area. Consider the crop establishment method as described above.

Step 5: Use a properly labeled grain collection bag to collect grain and run the plot combine harvester in the net harvest area. Make sure that grain loss during harvesting is minimal.

Step 6: If necessary, clean harvested grain, then weigh the total grain (g) using a digital balance and record the results.

Step 7: Immediately measure the grain moisture content (%) using a grain moisture meter.*

Note: * If there is no grain moisture meter available, grain moisture content can be determined for a representative sub-sample by weighing the sample fresh (at the same time as the total grain weight is determined) and drying it to constant weight either in an oven (typically at 75°C) or by sun and air. Then dry-weigh the sub-sample. The moisture content of the total grain weight is calculated by dividing the difference between fresh and dry weights of the sub-sample by the fresh weight of the sub-sample.

Note: If harvested grains are used for grain quality assessment, take a sub-sample and put it in a paper bag, ziplock bag or container before lab analysis.

1.3 Calculation

Step 1: Calculate the net harvest area in m^2

$$\text{Area } (m^2) = \text{Width (m)} \times \text{Length (m)} \tag{1}$$

Step 2: Convert the grain weight (net harvest area) to 12% moisture content using formula (2).

$$\text{Grain weight at 12\% moisture content (g)} = \text{Grain weight (g)} \times \frac{100 - \text{grain moisture content (\%)}}{88} \tag{2}$$

Step 3: Calculate grain yield in kg/ha (at 12% moisture content) using formula (3).

$$\text{Grain yield (kg/ha) at 12\% moisture content} = \frac{\text{Grain yield (g) of net harvest area at 12\% moisture}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (3)$$

Where the division by 1000 is the conversion of grams to kg; and the multiplication by 10,000 is the conversion from m^2 to ha.

Module 2: Measurement of aboveground biomass

2.1 Required equipment/materials

- Measuring tape
- Four pegs
- String or rope
- Cloth or woven polyethylene sacks
- Sickle
- Paper bag
- Ziplock bag
- Digital weighing balance
- Drying oven
- Data recording tools/sheet

2.2 Procedure

Step 1: Identify the physiological maturity stage in the field. Physiological maturity is the point at which grain reaches hard dough stage, i.e. when spikes completely lose their green color. This typically occurs a few days before harvestable maturity.

Step 2: Select net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

Step 3: Locate and mark the net harvest area by placing four pegs — one in each corner. When marking net harvest area, take into account crop establishment method. For example, if line-seeded, pegs should be placed centrally between rows on both sides. If plants are in random geometry (e.g. randomly broadcasted), only stems that fall *inside* the delineated area should be harvested.

Step 4: Record width (m) and length (m) of net harvest area. Consider the crop establishment method as described above.

Step 5: Cut all plants from the net harvest area at ground level. Make sure that no dried leaves or stems (including dead tillers) are lost. Remove other plants (weeds) and soil debris from harvested plants. Carefully place the harvested sample in large woven polyethylene sacks, with the spikes pointing downwards into the sacks. The bag should be pre-labeled (barcode, or details of location, farm number, year, treatment, date of sampling, plot number, etc.).

Step 6: Transport samples to a research station or any other place where samples can be properly processed, dried and stored before weighing.

Step 7: Thresh the harvested sample manually or mechanically to separate grains and straw.

Step 8: Separate harvested samples into grains and straw, and place the (grain and straw) sub-samples in separate bags that have been properly labeled. Record the fresh weight of grains (g) and straw (g) from the net harvested area using a digital balance.

If sample size is small, the whole samples can be put into the oven for measuring dry weight. If grain and straw samples are large (more than 1 kg), take a sub-sample of 100–200 g (depends on sample size) of each of grain and straw and put these into separate properly labelled paper bags. Weigh the sub-samples using a digital balance for both grain and straw sub-sample fresh weight (g).

Step 9: Oven-dry the samples of grains and straw at 75°C for 3 days or until they achieve stable weight. Record the oven-dried sub-sample weight of both grains and straw (g) immediately after taking out of the oven (do not let the samples rehydrate!).

Note: Avoid over-packing samples in the oven because good air circulation is needed for rapid and even drying.

Step 10: Grain and straw samples for quality analysis: take a 20–30 g sub-sample of oven-dried grain and place in a ziplock bag, and take a 20–30 g sub-sample of oven-dried straw and place it a paper bag. Both should be properly labeled. These samples can be used for further laboratory analysis.

2.3 Calculation

Step 1: Calculation of grain dry weight

For small samples

$$\text{Dry weight of grain (kg/ha)} = \frac{\text{Dry weight of grains (g)}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (4)$$

For large samples

$$\text{Dry weight of grain (kg/ha)} = \left[\frac{\text{Total fresh grain weight (g)} \times \dfrac{\text{Dry weight of grain sub-sample (g)}}{\text{Fresh weight of grain sub-sample (g)}}}{1000} \right] \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (5)$$

Step 2: Calculation of dry weight of straw

$$\text{Dry weight of straw (kg/ha)} = \left[\frac{\text{Total fresh straw weight (g)} \times \dfrac{\text{Dry weight of straw sub-sample (g)}}{\text{Fresh weight of straw sub-sample (g)}}}{1000} \right] \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (6)$$

Step 3: Calculation of total aboveground biomass (oven-dried weight) and harvest index

$$\text{Total aboveground biomass (kg/ha)} = \text{Dry weight of grains (kg/ha)} + \text{Dry weight of straw (kg/ha)} \qquad (7)$$

$$\text{Harvest index} = \frac{\text{Dry weight of grains (kg/ha)}}{\text{Total aboveground biomass (kg/ha)}} \qquad (8)$$

Contributor

Mina Devkota (International Center for Agricultural Research in the Dry Areas [ICARDA])

Suggested citation: Devkota M. 2022. Measurement of barley grain yield and aboveground biomass at maturity for crop cut at plot level, v1. Standard Operating Procedure 003. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d'Ivoire.

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Determination of cassava root yield and aboveground biomass by crop cut at plot level

SOP ID: 004

Version: 1

Crop: Cassava (*Manihot esculenta*)

Relevant KPIs: Productivity — yield; Resource use efficiency — nutrient use efficiency

R&D stage:

- Discovery stage (yield decomposition)
- Proof-of-concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Pilot stage (on-farm participatory trials, randomized control trial)

Scope of this SOP

Cassava is usually grown for its starchy storage roots; however, in many sub-Saharan African countries, cassava leaves are harvested and consumed as a vegetable. This SOP deals with the determination of storage root yield and aboveground biomass.

Cassava storage roots are commonly marketed as fresh roots and most yield data in the literature are expressed as fresh root yield, although this is in most cases not explicitly stated. This SOP provides guidelines to determine the storage root fresh and dry matter yields and the fresh and dry edible portion of the storage roots.

Cassava is planted from stem cuttings and thus the amount or length of marketable planting material is of commercial interest. This SOP provides guidelines to determine the mass and the length of planting material.

For agronomic and physiological purposes, the total plant biomass may be required. This SOP provides guidelines on how to determine the mass and the dry matter content of all aboveground plant material.

Definitions

Cassava storage root yield and aboveground biomass can be separated into several categories, and production or performance can be expressed in the following ways.

1. Cassava total fresh root yield: mass of all recovered storage roots, un-peeled and with root tips and tops *attached,* at any unspecified water content as found at the time of harvest, *including* secondary storage roots (Fig. 1) and all other storage roots irrespective of their suitability for consumption or processing, yet *excluding* rotten roots, over the harvest area (see section 1.1).
2. Cassava useful fresh root yield: mass of roots, un-peeled and with root tips and tops *attached*, at any unspecified water content as found at the time of harvest, *excluding* all roots not deemed suitable for consumption or processing (too small, crooked, rotten, unspecified damage), over the harvest area (see 1.2).
3. Cassava edible fresh root yield: mass of peeled roots with tips and tops *removed*, at any unspecified water content as found at the time of harvest, *excluding* all roots not deemed suitable for consumption or processing (too small, crooked, rotten, unspecified damage), over the harvest area (see 1.3).
4. Cassava total dry root yield: dry mass (0% water) of all recovered storage roots, un-peeled and with root tips and tops *attached*, *including* secondary storage roots and all roots irrespective of their suitability for consumption or processing, yet *excluding* rotten roots, over the harvest area (see Module 2).

5. Cassava useful dry root yield: dry mass (0% water) of un-peeled roots with root tips and tops *attached*, *excluding* all roots not deemed suitable for consumption or processing (too small, crooked, rotten, unspecified damage), over the harvest area (see Module 2).
6. Cassava edible dry root yield: dry mass (0% water) of *peeled* storage roots with tips and tops *removed*, *excluding* all roots not deemed suitable for consumption or processing (too small, crooked, rotten, unspecified damage) (see Module 2).
7. Cassava total aboveground biomass yield: total dry mass (0% water) of the planting stake, the stems, branches, fruit (if present) and leaves (see Module 3).

Important note: This SOP is not suitable for systems in which roots are sequentially harvested from cassava plants, by digging out and cutting off individual roots, yet without uprooting the entire plant (often called 'milking').

Cassava can be harvested over a long period, depending on the suitability of the different varieties: very early bulking varieties can be harvested from 6 months after planting (MAP), while varieties resistant to root rot may remain in the field for more than 2 years. Root and aboveground yields cannot be validly compared if the cassava was harvested at different crop ages. For this reason, the expression of the yield requires a correction for the time the crop occupied the field (see Module 5).

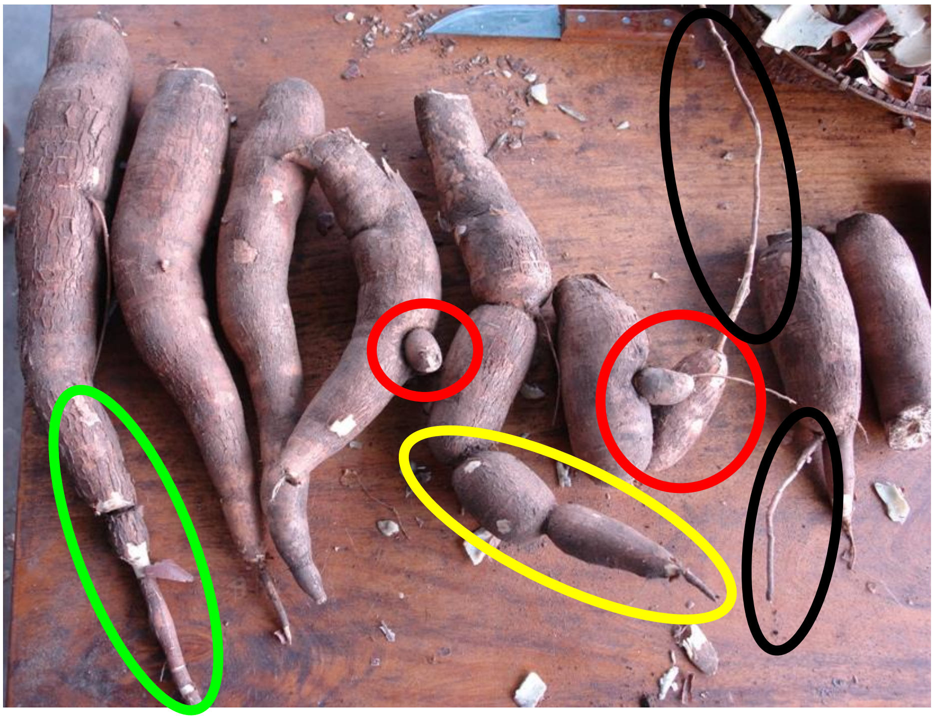


Figure 1. Cassava storage roots with small secondary roots attached **O**, *long slowly tapering tips* **O**, *pearl-string-like deformations* **O**, *and non-storage roots* **O**.

Some of these roots may not be used for processing yet are part of the total fresh yield; non-storage roots are not part of the total root yield. Hereafter, the term 'root' refers to storage roots only.

The definitions (above) show that cassava root yield can be expressed in several ways. Thus, the objective of the trials should determine which portion and category of the cassava roots is required to enable valid comparisons. For correct comparisons between varieties and treatments, and to relate cassava productivity to that of other crops, the most appropriate yield categories are the "useful root dry matter" and the "edible root dry matter" yields, respectively. Although only roots prepared for processing, i.e. peeled and tips and tops removed, are actually used for industrial purposes and in the human food chain, researchers continue to express cassava yields using the mass of raw roots. This can be compared with expressing maize yields on the cob, with the husks attached, at an unspecified water content, something that would not be accepted by peers and journals. This SOP is thus an appeal to consider the way cassava yields are expressed and to choose a category that presents the yield in an unbiased manner and validly comparable across varieties, treatments and other crops.

Required equipment/materials

- Data collection tools such as Open Data Kid (ODK) forms or any other electronic collection forms, paper data forms, stationery*
- Field or trial plan*
- Pegs to delineate the net plot
- Cutlasses/machetes or large knives to dissect the plant and remove roots
- Spade or other digging tool in case roots cannot be uprooted by pulling the planting stake
- Large containers, buckets, basins or bags to transport roots from the field and for weighing them
- Caliper to determine root diameter (useful root yield)
- Knives to cut off non-storage roots, tops and tips, and to peel (edible root yield)
- Brushes to clean roots of soil (mostly on soils with a high clay content)
- Balance to weigh raw roots (at least 25 kg capacity and 0.01 kg resolution)
- Balance to weigh root and aboveground parts sub-samples for dry matter determination (at least 1 kg capacity and 1 g resolution)
- Electric or engine-driven shredder (recommended if available and aboveground biomass is sampled)
- Wooden or nylon block and tarpaulin to manually cut and collect root and shoot samples
- Paper bags for the fresh sub-sample
- Ruler or tape measure for length of planting material
- Forced-draft dying oven (in case dry matter yield is determined)
- Gravimetric balance (in case the dry matter and starch content are estimated by indirect methods)

* Required for all operations.

Module 1. The harvest procedure

The sequence of the cassava harvesting activities depends on the objectives of the trial and the data required.

If the harvest is for the storage roots only and the aboveground shoot portion is of no interest, it is most convenient to cut the stems at a height that allows for easy pulling and uprooting and to discard the remaining stems, branches and leaves from the plot. To determine the storage root yield, first all storage roots need to be removed from the soil (section 1.1), then the different root yield categories are determined by removal of useless roots (1.2) and then the removal of the non-edible and non-processed parts of the storage roots (1.3). To obtain the dry matter yield of any selected yield category, root sub-samples of the respective root types need to be taken and dried (Module 2).

If the aboveground biomass is to be determined, we recommend you first harvest the shoot portion according to the required dissection protocol (see Module 3). Due to the very high variability of water and nutrient contents in green versus lignified (woody) shoot parts, separation is recommended at least into green branches with leaves and lignified stems and branches. This is best done by first breaking the green branches off the plant and processing them (see 3.1). The lignified main stems and branches are then cut off and processed. It is advisable to at least partially uproot the plants before cutting off the main stems to facilitate the root harvest. Partial uprooting means lifting the root stock, so it dislodges from the soil but leaving the roots in the soil, so the plant remains standing. The main stems can then be cut off and processed and later the storage roots can be pulled from the soil with only the old planting stake remaining attached to them.

Staff and supervisors conducting the harvest need to consider this before harvesting, as uprooting first and then harvesting shoot parts will impair the ability of staff to move in the plot and can lead to loss of material and contamination with soil.

1.1 Cassava total fresh root yield

1.1.1 Required equipment/materials

- Pegs to delineate the net plot
- Cutlasses/machetes or large knives to dissect the plant and remove roots
- Spade or other digging tools in case roots cannot be uprooted by pulling the planting stake

- Large containers, buckets, basins or bags to transport roots from the field and for weighing them
- Brushes to clean roots of soil (mostly on soils with a high clay content)
- Balance to weigh raw roots (at least 25 kg capacity and 0.01 kg resolution)

1.1.2 Sampling

Step 1: Remove the unnecessary aboveground biomass.

Step 2: The cassava total fresh root yield is determined by uprooting all plants in the delineated net harvest area.

Step 3: The storage roots are then cut off the planting stake. Some varieties have a narrow piece of root between the planting stake and the top of the storage root, while some other varieties form storage roots directly attached to the planting stake. In the former, the root should be cut off at the end of the connecting piece towards the top of the root; in the latter, the roots should be cut off flush with the planting stake, yet such that no planting stake tissue is attached to the roots. All non-storage roots (Fig. 1 **O**) are cut off the storage roots.

Step 4: Storage roots broken off the planting stake when uprooting are dug up and added to the total.

Step 5: All non-storage roots are cut off. If a storage root has no obvious end but tapers out over a long portion of the distal end (Fig. 1 O), then the cut-off point is where the diameter of the root is below a size considered suitable for processing (usually around 15–20 mm). We propose you cut where the diameter becomes < 20 mm. If a smaller or larger diameter is used, this needs to be recorded.

Step 6: Before weighing the roots, all soil must be removed from their surfaces.

If the dry matter yield of the total roots is required refer to 2.1.2 for sampling and processing and to 2.1.3.1 for calculations.

Note: An often observed way to show cassava root yield is the removal of the entire root stock with the planting stake and parts of the stem still attached (Fig. 2). The mass obtained in this way does not reflect the cassava total root yield but overestimates the yield because of the attached planting stake, part of the stems and possibly soil trapped between the roots — this is not suitable to be weighed and expressed as yield.

Figure 2. Cassava root stock including planting stake and stem and probably soil and unsuitable roots

1.1.3 Calculation

The fresh root mass is recorded in kg per net plot. The total fresh root yield in megagrams (tonnes) per hectare (t/ha) is calculated as:

$$\text{Total fresh root yield (t/ha)} = \frac{\text{Total fresh root mass (kg)}}{1000} \times \frac{10{,}000}{\text{Net plot size (m}^2\text{)}} \qquad (1)$$

Where the division by 1000 is the conversion from kg to tonnes and the multiplication with 10,000 the conversion from m^2 to ha.

1.2 Cassava useful fresh root yield

1.2.1 Required equipment (in addition to 1.1.1)

- Caliper to determine root diameter and cut-off point (useful root yield)

1.2.2 Sampling

The useful cassava fresh root yield is obtained by removing all roots and root materials deemed unsuitable for consumption or processing from the total roots as determined in 1.1. The root mass placed on a balance to determine the useful fresh root yield must only consist of roots that are acceptable for processing or consumption. The following criteria shall be used to exclude roots or root parts from being considered useful or fit for consumption or processing:

- roots with a diameter < 20 mm
- roots with a mass < 140 g
- misshapen roots (see Fig. 1 O and O) and requiring unacceptably long time to peel
- roots with a large portion of rotten tissue
- lignified root portions (usually in older crops from the top of the root).

If the dry matter yield of the useful roots is required refer to 2.1.2 for sampling and processing and 2.1.3.2 for calculations.

Unfortunately, the types of roots and their sizes locally considered unsuitable for processing or consumption differ widely. Small, crooked or pearl-string roots (Fig. 1) may be regarded as worthwhile to be peeled and processed or used as animal feed in some places, while they are left in the field in others. Therefore, it is acceptable to deviate from the above exclusion criteria but in such cases, a protocol is required describing the locally relevant criteria by which roots are deemed unsuitable and thus removed from the useful yield.

A special case is large roots with localized mechanical damage or rot, which are not entirely useless. Here the damaged or rotten portion of the root should be cut off and discarded and the useful portion should be included with the other useful root mass.

Any roots deemed unsuitable for processing or consumption but used as animal feed or for any other benefit-generating purpose, may not be part of the mass weighed as useful fresh root yield but need to be weighed and reported separately.

1.2.3 Calculations

The calculation of the cassava useful fresh root yield follows the same procedure as in 1.1.

$$\text{Useful fresh root yield (t/ha)} = \frac{\text{Useful fresh root mass (kg)}}{1000} \times \frac{10{,}000}{\text{Net plot size (m}^2\text{)}} \qquad (2)$$

Where the division by 1000 is the conversion from kg to t and the multiplication with 10,000 the conversion from m^2 to ha.

The proportion and percentage of roots unsuitable for consumption or processing is calculated as:

$$\text{Proportion unsuitable root fresh mass} = 1 - \frac{\text{Useful fresh root yield (t/ha)}}{\text{Total fresh root yield (t/ha)}} \qquad (3)$$

and

$$\text{Unsuitable root fresh mass (\%)} = 1 - \frac{\text{Useful fresh root yield (t/ha)}}{\text{Total fresh root yield (t/ha)}} \times 100 \qquad (4)$$

1.3 Cassava edible fresh root yield

To validly estimate the edible fresh root mass, all the useful roots need to be peeled and tops and tips cut off. This, however, is extremely labor intensive. To reduce the labor, a large sub-sample of the useful roots can be weighed, peeled, and have their tops and tips removed.

1.3.1 Required equipment (in addition to 1.1.2)

- Knives to cut off non-storage roots, tops and tips, and to peel (edible root yield)

1.3.2 Sampling

Step 1: Depending on the number of useful roots, decide whether all the roots will be peeled and cut or a large sub-sample will be used.

Step 2: If all the useful roots are used to obtain the edible fresh root yield, the tips and tops of the roots need to be cut off. The tops (the part pointing toward the planting stake) of non-lignified roots are cut off such that it is easy to start peeling – usually about 1–2 cm below the top. However, in older cassava and under certain site conditions, the tops may be lignified and thus are not edible and need to be cut off at the position where the lignification stops. In some cases, this can be several centimeters into the root. The tips are the continuation of the storage roots as feeder roots. While in most varieties there is an abrupt end of the storage root and a continuation at a much smaller diameter, there are varieties and sites in which the roots taper without a clear transition from storage to feeder root. In such cases the roots are cut off as soon as the diameter is below 20 mm. From the cut roots the peel is removed.

Step 3: If the number of useful roots is too large, take a large sub-sample (about 5–10 kg) from the useful cassava fresh root yield sample and process as in Step 2.

Only peeled and cut roots in the state in which they would be prepared to be eaten or in which they would enter the processing procedure may be considered (Fig. 3). Peeling and cut-off losses may exceed 25% of the useful root mass, depending on variety and root diameter and are usually not less than 20% (Hauser *et al.*, 2020).

If the dry matter yield of the edible roots is required, refer to 2.1.2 for sampling and processing, and to 2.1.3.3 for calculations.

1.3.3 Calculations

If the total amount of the useful roots was peeled and cut, the calculation of the cassava edible fresh root yield follows the same procedure as in 1.1.

$$\text{Edible fresh root yield (t/ha)} = \frac{\text{Edible fresh root mass (kg)}}{1000} \times \frac{10{,}000}{\text{Net plot size (m}^2\text{)}} \qquad (5)$$

Where the division by 1000 is the conversion from kg to t, and the multiplication by 10,000 the conversion from m^2 to ha.

The calculation of the proportion and percentage of peeling and cut-off losses relative to the useful fresh root yield is as follows:

$$\text{Proportion of peel and cut-off fresh mass} = 1 - \frac{\text{Edible fresh root yield (t/ha)}}{\text{Useful fresh root yield (t/ha)}} \qquad (6)$$

and

$$\text{Peel and cut-off fresh mass (\%)} = 1 - \frac{\text{Edible fresh root yield (t/ha)}}{\text{Useful fresh root yield (t/ha)}} \times 100 \qquad (7)$$

If a sub-sample of the useful roots was taken, peeled and cut, the proportion of edible fresh root mass in the useful fresh root mass needs to be calculated as:

$$\text{Proportion of edible fresh roots} = \frac{\text{Edible fresh root mass (kg)}}{\text{Useful fresh root mass (kg)}} \qquad (8)$$

The edible fresh root yield is then calculated as:

$$\text{Edible fresh root yield (t/ha)} = \text{Useful fresh root yield (t/ha)} \times \begin{array}{c}\text{Proportion of edible root}\\ \text{mass in useful root mass}\end{array} \qquad (9)$$

Figure 3. Peeled cassava with feeder roots, tips and tops removed and ready for processing

Module 2. Cassava total, useful and edible dry root yield

Important note: If the dry matter content of the roots is to be determined:

- avoid the roots being exposed to heat and sunshine after uprooting
- the roots need to be properly cleaned of soil before sub-sampling and weighing
- when cutting and mixing the root slices, do not delay between cutting, mixing and weighing the fresh mass.

Under hot and dry conditions, the large cut surfaces of the sample will lose water very rapidly and thus cause erroneous overestimations of the dry matter content. If the nutrient content is to be determined, all samples should be dried in a forced-draft drying oven at temperatures below 65°C to prevent alterations of the sample. If only dry matter is required, the temperature can be as high as 105°C.

2.1 Principal method

2.1.1 Required equipment (in addition to 1.1.3)

- Knives to cut off non-storage roots, tops and tips, and to peel (edible root yield)
- Brushes to clean soil from roots (mostly on soils with a high clay content)
- Balance to weigh root sub-samples for dry matter determination (at least 1 kg capacity and 1 g resolution)
- Wooden or nylon block and tarpaulin to aid manual cutting of root samples
- Paper bags for the fresh sub-sample
- Forced-draft dying oven.

2.1.2 Sampling

Step 1: The *cassava total, useful and edible dry root yields* are obtained by sub-sampling an appropriate number of roots (we recommend 5–10) of representative sizes from the respective root categories, i.e. total roots, useful roots, edible roots.

Step 2: The roots are cut into 10–15 mm thick slices on a clean surface (wooden or nylon block with a tarpaulin under it).

Step 3: A minimum mass of about 1000 g (1 kg) of root slices is cut and thoroughly mixed. About 400–500 g of this mixed sample are weighed fresh and dried in a forced-draft oven to constant mass, and then weighed dry.

2.1.3 Calculations

The proportion and percentage of dry matter in total, useful and edible roots is calculated as follows.

2.1.3.1 For total roots

$$\text{Proportion dry matter in total roots} = \frac{\text{Dry mass of total roots sub-sample (g)}}{\text{Fresh mass of total roots sub-sample (g)}} \tag{10}$$

and

$$\text{Dry matter in total roots (\%)} = \frac{\text{Dry mass of total roots sub-sample (g)}}{\text{Fresh mass of total roots sub-sample (g)}} \times 100 \tag{11}$$

The *total dry root yield* is calculated as:

$$\text{Total dry root yield (t/ha)} = \text{Total fresh root yield (t/ha)} \times \text{Proportion of dry matter in total roots} \tag{12}$$

or

$$\text{Total dry root yield (t/ha)} = \frac{\text{Total fresh root yield (t/ha)} \times \text{Dry matter in total roots (\%)}}{100} \tag{13}$$

2.1.3.2 For useful roots

$$\text{Proportion dry matter in useful roots} = \frac{\text{Dry mass of useful roots sub-sample (g)}}{\text{Fresh mass of useful roots sub-sample (g)}} \tag{14}$$

and

$$\text{Dry matter in useful roots (\%)} = \frac{\text{Dry mass of useful roots sub-sample (g)}}{\text{Fresh mass of useful roots sub-sample (g)}} \times 100 \tag{15}$$

The *cassava useful dry root yield* is calculated as:

$$\text{Useful dry root yield (t/ha)} = \text{Useful fresh root yield (t/ha)} \times \text{Proportion of dry matter in useful roots} \tag{16}$$

or

$$\text{Useful dry root yield (t/ha)} = \frac{\text{Useful fresh root yield (t/ha)} \times \text{Dry matter in useful roots (\%)}}{100} \tag{17}$$

2.1.3.3 For the edible roots

$$\text{Proportion dry matter in edible roots} = \frac{\text{Dry mass of edible roots sub-sample (g)}}{\text{Fresh mass of edible roots sub-sample (g)}} \tag{18}$$

and

$$\text{Dry matter in edible roots (\%)} = \frac{\text{Dry mass of edible roots sub-sample (g)}}{\text{Fresh mass of edible roots sub-sample (g)}} \times 100 \tag{19}$$

The *cassava edible dry root yield* is determined as:

$$\text{Edible dry root yield (t/ha)} = \text{Edible fresh root yield (t/ha)} \times \text{Proportion of dry matter in edible roots} \tag{20}$$

or

$$\text{Edible dry root yield (t/ha)} = \frac{\text{Edible fresh root yield (t/ha)} \times \text{Dry matter in edible roots (\%)}}{100} \tag{21}$$

2.2 Estimating edible dry root yield from useful dry root yield

An alternative procedure to approximate the edible dry root yield is the post-drying peel removal from a dry matter sample of the *useful cassava fresh roots*. If the *useful cassava fresh root yield* was determined and dry matter samples were taken from the useful roots, it is possible to approximate *edible root dry matter yield* from these samples. For this, the dry useful root sub-sample, comprising peel and root cores, needs to be separated into peel and root cores and the two fractions weighed separately. In most cassava varieties this is relatively easily done because the peel comes off the core during drying. However, the procedure of removing the peel may be time-consuming and it needs to be complete. It must be considered that this approach does not consider the mass of root tops and tips that are cut off to determine the exact edible root dry matter yield, thus is a slight overestimation. Root top and tip cut-off losses are around 10% of the unpeeled root fresh mass (Hauser *et al.*, 2020). Assuming that there is no significant difference in dry matter content between the cut off tops and tips and the remaining root, the indirectly determined edible dry root yield can be further approximated by considering this 10% reduction. To do this the useful fresh root yield in equation (23) is multiplied by 0.9. The ratio of root core dry mass to peel dry mass or the proportion of root core (being the edible portion of the roots) is required and calculated as:

$$\text{Proportion dry root core (edible root) mass} = \frac{\text{Dry root core mass in useful roots sub-sample (g)}}{\text{Total useful roots sub-sample dry mass (g)}} \tag{22}$$

To calculate the approximate edible dry root yield:

$$\text{Edible dry root yield (t/ha)} = \text{Useful fresh root yield (t/ha)} \times \text{Proportion of dry matter in useful roots} \times \text{Proportion of dry root core mass in the useful roots sub-sample} \tag{23}$$

2.3 Indirect estimates of cassava root dry matter and starch content

The dry matter and starch content of the cassava roots are the two most important quality criteria, and the processing industry is increasingly setting fresh root prices according to dry matter and starch content. The dry matter content and the starch contents of cassava roots are closely correlated and thus the dry matter content is a very reliable indicator of starch content. Although the root mass delivered is of importance, the starch content modifies the price per tonne (megagram) and as such this variable is of importance to farmers and researchers.

2.3.1 Required equipment

- Gravimetric balance

Or, if a commercial gravimetric balance is not available

- Balance to weigh raw roots (at least 5 kg capacity and 0.01 kg resolution)
- Large container with water to submerge the roots
- Strong, yet light netting to hold roots
- Small table with a hole in the middle (see note below).

Note: Any balance with a hook at the bottom to attach the net would be suitable to serve as a gravimetric balance. You need a small table with a hole in the middle to pass the string attaching the net to the balance.

2.3.2 Sampling and weighing procedure

The alternative to dry matter determination in cassava roots by oven-drying is the specific gravity method. This requires weighing a certain fresh root mass (not less than 3 kg is recommended) in air and then weighing the same roots completely submerged in water.

Step 1: Weigh the net in air and under water and record the mass in both media

Step 2: Place about 5 kg of clean roots into the net and weigh them in the air; record the mass

Step 3: Attach the net to the bottom hook of the balance and submerge the roots, such that they are completely under water; record the mass under water.

2.3.3 Calculations

The specific gravity (SG) is then calculated as:

$$\text{Specific gravity (SG)} = \frac{\text{Fresh root mass in air}}{(\text{Fresh root mass in air} - \text{Fresh root mass in water})} \tag{24}$$

There are many different equations available to convert the specific gravity (SG) to the dry matter content of cassava roots. The following equations are a small selection based on research verified with oven drying of the samples. The dry matter content in % is calculated as follows.

Dry matter content (%) = (158.3 × SG) – 142.0. (Ikeogu *et al.*, 2017) (25a)

Dry matter content (%) = (188.6 × SG) – 175.5. (Teye *et al.*, 2011) (25b)

Dry matter content (%) = (192.89 × SG) – 180.22 (Maraphum *et al.*, 2021) (25c)

To express the cassava root dry matter content as a proportion, equations 25a, b, c are divided by 100 as follows.

$$\text{Proportion of dry matter in roots} = \frac{(158.3 \times SG) - 142}{100} \tag{26a}$$

$$\text{Proportion of dry matter in roots} = \frac{(188.6 \times SG) - 175.5}{100} \tag{26b}$$

$$\text{Proportion of dry matter in roots} = \frac{(192.89 \times SG) - 180.22}{100} \tag{26c}$$

The starch content ranges around 80% of the root dry matter and can be approximated by multiplying equations 25a, b, c by 0.8.

Alternatively, the starch content can be calculated using the specific gravity (SG) as follows.

Starch content (%) = (159.1 × SG) – 147 (Maraphum *et al.*, 2020) (27a)

Starch content (%) = (210.8 × SG) – 213.4
(Institute of Economic Crops of Guangxi Academy of Agricultural Sciences, 2016) (27b)

To express the cassava starch content as a proportion, equations 27a and b are divided by 100 as follows.

$$\text{Proportion of starch in roots} = \frac{(159.1 \times SG) - 147}{100} \tag{28a}$$

$$\text{Proportion of starch in roots} = \frac{(210.8 \times SG) - 213.4}{100} \tag{28b}$$

For equation 27b, the values of slope, 210.8 (a), and the constant, 213.4 (b), were indicated as the preferable constants, while the full range was: $205 \leq a \leq 216$, and $208 \leq b \leq 219$.

It thus appears advisable to run a set of parallel dry matter determinations by oven-drying the same samples to verify the slope and absolute term in the equation.

Module 3. Harvest of aboveground cassava plant parts

Depending on the objectives of a trial, the total biomass (excluding fine roots) of a cassava crop may need to be determined. This protocol deals with a total biomass harvest only when in conjunction with the final storage root harvest. For staggered harvests during the growing period, other specific protocols need to be followed.

The aboveground biomass of cassava is highly variable in dry matter and nutrient content. Harvesting leaves, stems, etc., to determine fresh matter alone thus makes no sense as the obtained data give no indication of the real dry matter yield.

If the cassava nutrient uptake is required, the least intensive approach is a separation of the shoot matter into lignified and green parts. At the usual crop age for storage root harvest, the main stems and the primary branches are usually lignified, have a gray to brown skin and no longer bear leaves. Most younger branches and those still bearing leaves are usually green. The latter usually have higher water and nutrient contents than the lignified parts.

3.1 Shoot harvest simple (lignified versus green shoots)

3.1.1 Required equipment

- Cutlasses/machetes or large knives to dissect the plant
- Balance to weigh raw shoot parts (at least 25 kg capacity and 0.01 kg resolution)
- Balance to weigh aboveground parts sub-samples for dry matter determination (at least 1 kg capacity and 1 g resolution)
- Electric or engine-driven shredder (recommended if available)
- Wooden or nylon block and tarpaulin to aid manual cutting of shoot samples
- Paper bags for the fresh sub-sample
- Forced-draft dying oven

3.1.2 Sampling

Step 1: Break or cut all green branches off the plant and weigh fresh.

Step 2: Select several (3–6) complete branches with the leaves still attached and shred into small (1–2 cm) pieces.

Step 3: Mix the shredded material thoroughly and take a 400–500 g sub-sample and weigh fresh.

Step 4: Oven-dry the sub-sample in a forced-draft oven until constant mass and weigh dry.

Step 5: Cut the lignified main stems and branches off the planting stake and weigh fresh.

Step 6: Follow steps 2 to 4 above but for the lignified material.

3.1.3 Calculations

The proportion of dry matter in any plant part is calculated as in equation (29):

$$\text{Proportion of dry matter in the plant part sub-sample} = \frac{\text{Dry mass of the plant part sub-sample (g)}}{\text{Fresh mass of the plant part sub-sample (g)}} \qquad (29)$$

The dry matter yield of any cassava plant part is calculated as:

$$\text{Cassava plant part dry matter yield (kg/ha)} = \text{Plant part fresh mass in the net plot (kg)} \times \text{Proportion of dry matter in the plant part sub-sample} \times \frac{10{,}000}{\text{Area of the net plot (m}^2\text{)}} \qquad (30)$$

Where the factor 10,000 is the conversion from m^2 to ha.

3.2 Shoot harvest with multiple and variable dissections

The cassava shoot can be separated into a variety of sections and scientists will need to choose how they need to separate the shoot according to their objectives. Therefore, scientists need to describe the way the shoot is dissected and follow the general rules in determining the total biomass of each aboveground plant part and its dry matter content. In all cases, the procedure to determine the dry matter content and the dry matter yield of any plant part follows the procedure described under 2.1.2 for roots and 3.1.2 for shoot parts.

3.3 Optional data collection on shoots before the harvest

Once the net plot area to be harvested is determined and marked, the number of plants and the number of main stems is counted. Main stems are those stems emerging directly from the planting stake. Where deemed important, the number of primary branches can be counted — primary branches are those emerging from a main stem. In addition, if required by the trial objectives, the branching level can be determined on selected plants. This is done by following from a main stem to the first branch, then follow the first branch until it branches again and so on until the branch is not branching again; the number of branchings is recorded.

Module 4. Secondary products

4.1 Cassava planting material yield (main stem and lignified branch length)

Cassava planting material is usually sold in stem bundles of 50 to 100 stems and at a specified length. In most of Africa and especially in Nigeria, bundles are usually 1 m long, while in many Asian countries cassava planting material is sold cut to the length of the final planting stake. However, the total length of main stems or lignified branches is of economic interest. To estimate the quantity of planting material, the length of the sub-sampled lignified main stems and branches (as determined in 3.1.2, Step 5) is measured with a ruler or tape measure.

4.1.1 Required equipment

- Balance to weigh main stems and lignified branches (at least 25 kg capacity and 0.01 kg resolution)
- Ruler or tape measure to measure the length of planting material.

4.1.2 Sampling

This procedure requires counting the number of main stems in the net plot.

Step 1: Remove a number of representative complete main stems with lignified branches (we recommend 5–10 stems) from the stems of a plot.

Step 2: Determine whether all the selected material meets the criteria for planting material (diameter, nodes, level of lignification).

Step 3: Where the entire sample of lignified main stems and branches adheres to the planting material criteria, the total mass of the stems and lignified branches sub-sample is weighed.

Step 4: The total length of the stems and lignified branches sub-sample is measured with a tape or ruler.

Step 5: Where not all material of the stems and lignified branches in the sub-sample meets the planting material criteria, all material that does not meet the criteria is removed from the lignified main stems and branches sub-sample.

Step 6: The remaining planting material sub-sample is weighed.

Step 7: The total length of the remaining planting material (i.e. the stems and lignified branches sub-sample weighed in Step 6) sub-sample is measured with a tape or ruler.

4.2 Calculations

In both cases, the length of planting material produced per hectare is calculated as:

$$\text{Length of planting material (m/ha)} = \frac{\text{Length of planting material (m)}}{\text{Mass of planting material (kg)}} \times \text{Yield of lignified main stems and branches (t/ha)} \times 1000 \quad (31)$$

Where the factor 1000 is the conversion of t/ha to kg/ha.

Module 5. Time-corrected root yield calculation

Depending on variety, market situation and farmers' needs, cassava can be harvested at 6 months after planting (MAP), though many varieties are being kept in the field for 12–18 months or longer. While this is an opportunity for farmers to stretch or set the harvest to the most convenient time, it is also a major source of error in comparisons across trials. Because cassava growing periods may vary widely, the time factor in yield formation needs to be considered.

The determination of yield per unit time can only be conducted for fields that are harvested within a short time window. Fields that are harvested over long periods, or where individual roots are removed from rootstocks without uprooting the whole plant (milking), as is common in subsistence systems, cannot be considered here.

Generally, the cassava yield should be expressed per unit area and per unit time, and therefore requires the information on the actual period of growth.

It is proposed to quote cassava root yields as *x* t/ha within *z* months and give the yield per ha and per month (*y* t/ha per month).

$$\text{Time-corrected cassava root yield (t/ha per month)} = \frac{\text{Cassava root yield (t/ha)}}{\text{Length of growing period (months)}} \quad (32)$$

This can be used for any category of roots.

Thus, a cassava total root yield of 12 t/ha attained within 10 months would be equivalent to 1.2 t/ha per month, a yield of 9 t/ha attained within 6 months would be equivalent to 1.5 t/ha per month, and a yield of 20 t/ha attained in 18 months would be equivalent to 1.111 t/ha per month.

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Contributor

Stefan Hauser (International Institute of Tropical Agriculture [IITA])

Suggested citation: Hauser S. 2022. Determination of cassava root yield and aboveground biomass by crop cut at plot level, v1. Standard Operating Procedure 004. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d'Ivoire.

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Measurement of maize grain yield and aboveground biomass at maturity by crop cut at plot level

SOP ID: 005

Version: 1

Crop: Maize/corn (*Zea mays*)

Relevant KPIs: Productivity — yield

R&D stage (example of activities):

- Pilot stage (nutrient-omission trials, on-station and on-farm in small plots, or other agronomic trials)
- Proof-of-concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Scaling stage (on-farm trials)

Required equipment

- Scales/balances that can accurately measure weights of smaller samples (grain and stover moisture sub-samples) and larger samples (plant sample, grain sample, stover sample)
- Sheller (manual or mechanized)
- Lengths of pre-measured twine (60 cm recommended)
- Machete or large knife
- Large cloth sacks
- Medium-sized cloth bags
- Large paper (grocery) bags
- Markers and labels
- Plastic bucket
- Data recording notebook/sheet and pen/pencil
- Grain moisture meter (optional)

See also the equipment list in SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

All measuring equipment requires calibration. Proper calibration requires additional equipment not listed here. We recommend consulting guidance published by The United States Bureau of Reclamation (USBR, 1989a,b,c): USBR-1000-89, USBR-1012-89, USBR-1020-89; the National Institute of Standards and Technology Office of Weights and Measures (NIST OWM, 2019a,b,c,d,e) standard operating procedures Nos 4, 5, 7, 8, 28; NIST Special Publication 250-31 (Davis, 1989); NIST Handbook 44 (Butcher *et al.*, 2022); and NIST Handbook 159 (Lee and Olson, 2017).

Record information about each measuring instrument: manufacturer, model number, date of last calibration certification, precision, weight limits, etc.

At each experimental site, set up a processing area in the field. This area should be equipped with calibrated measuring equipment. Reserve at least one bag of each type as well as a few lengths of twine and any labels to tare the scales.

Module 1: Aboveground biomass measurements at physiological maturity

Measurements in this module are used to calculate harvest index and average aboveground biomass per plant. These metrics are used in Module 3 to calculate biomass yield per unit area. Conventionally, measurements in this module are performed at growth stage R6 on a small sample of plants from the harvest area in each experimental unit.

1.1 Procedure

Step 1: Delineate the harvest area and record its dimensions.

We recommend determining the size of the harvest area based on characteristics of individual experimental sites. Important factors are plant density and yield level (see SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations).

Step 2: Determine the number of plants to sample.

We recommend a minimum of six plants (Kladivko *et al.*, 2014); however, in low-yielding treatments, more plants may be needed to provide sufficient material to be within the calibrated ranges of measuring equipment. We recommend testing the number of plants needed by sampling the border area of the treatment that is likely to be the lowest yielding. Start with six plants and go through all the steps in this module to determine whether there is sufficient material for all measurements. If not, incrementally add more plants, running through all steps each time, to determine the number of plants required. Once the number of plants required is determined, use this number consistently across all treatments at a given site. In the following steps, we use six plants, but substitute the number you determine to be required. *Do not use less than six plants*.

If barren plants are present, barren and productive plants will require separate samples. Identify barren plants by first determining whether an ear has been formed. If not, the plant is barren. If an ear was formed, the plant is barren if no grain has fully developed on the cob. Examine the rigidity of the ear. A thin, flexible ear is indicative of poor grain fill or barrenness. Squeeze the ear gently to feel for grain and, if necessary, gently and carefully peel back part of the husk to visually inspect the ear. If no fully developed grain is present on the ear, the plant is barren.

When determining the number of plants that need to be sampled, perform this step for both barren and productive plants, since the numbers of plants required may differ.

Step 3: Record the growth stage.

Scientific convention is to measure aboveground biomass at physiological maturity (R6). Determining when this growth stage occurs requires frequent (daily) monitoring after stage R5. A maize *plant* is at R6 when 95% or more of the kernels in the ear have formed a black layer. For a *population* of maize plants, R6 is defined as 50% of all plants at this stage of development. On each day after a few plants have reached R6, evaluate 10 representative plants to determine the percentage at R6. Because destructive sampling is involved, take measurements from plants in border areas (outside the harvest area). Do this each day until 50% of the plants are at R6. When daily monitoring is not possible, determine the growth stage on the day of sampling and record. If the day of physiological maturity has passed, indicate this in your records (i.e. “post physiological maturity”).

Step 4: Measure the fresh weight of the six-plant samples for both barren and productive plants.

Use a large knife to cut six representative plants about 2 cm above the soil surface from random locations within the harvest area. Representative plants should have the same stalk diameter, plant health, and stage of development as the majority of plants in the harvest area. Tie the plants together to form a bundle, attach a label, and weigh on a tared scale. Record weight in grams. Do this separately for barren and productive plants — one bundle for each.

Step 5: From the bundle of productive plants only, remove the ears from the six-plant sample.

Untie the bundle of productive plants, carefully remove the ears, keeping the husks attached to the stalks. Ensure all plant material other than the ears stays together. Re-tie the bundle, ensuring the label is attached. Reserve.

The following steps are for measurements on maize ears taken from the productive plants.

Step 6: Measure the number of ears in the six-plant sample of productive plants.

Count and record the number of ears.

Step 7: Measure the fresh weight of the six-plant ear sample.

Place ears into a large labeled paper bag and weigh on a tared scale. Record the weight in grams.

Step 8: Measure the fresh weight of the six-plant grain sample.

Using a sheller, remove the grain from the ears. Shell into a plastic bucket, ensuring no grain is lost. Pour all the grain into a large labeled paper bag and weigh on a tared scale. Record the weight in grams. Reserve.

Step 9: Measure the fresh weight of the six-plant cob sample.

Place the shelled cobs into a large paper bag and weigh on a tared scale. Record the weight in grams. Transport to a drying facility.

The following steps differ depending on whether or not a calibrated grain moisture meter is available.

If a moisture meter is available:

Step 10: Measure the six-plant grain sample moisture.

Mix the six-plant grain sample thoroughly. Follow the manufacturer's instructions and record grain moisture as a percentage.

If a moisture meter is not available or as an additional quality-control step:

Step 11: Take a sub-sample from the six-plant grain sample and measure its fresh weight. This sub-sample will be used for moisture determination.

Mix the six-plant grain sample thoroughly. Place a medium-sized cloth bag on the scale and tare. Add grain until there is at least 300 g in the bag. Record the exact weight in grams. Transport to a drying facility.

The following steps are for measurements on bundled plant material (both barren and productive).

Step 12: From the bundle of productive plants only, measure the fresh weight of the six-plant stover sample (the material left after the ears were removed in Step 5). For barren plants, this step is not necessary, since the corresponding measurement was already taken in Step 4.

Weigh the bundle on a tared scale. Record the weight in grams.

Step 13: Take separate sub-samples from barren and productive bundles and measure their fresh weights. These sub-samples will be used for moisture determinations.

For each bundle, untie the twine and select three representative plants. Remove the leaves from those plants and cut into small (5 cm) pieces and place in a labeled, medium-sized cloth bag. Remove and cut the husks (plus barren ears in the case of barren plants) into small pieces and add to the leaves. Cut the remaining stalks and add to the rest of the cut material. Ensure no plant material is lost during cutting. Weigh immediately on a tared scale. Record the weight in grams. Perform this procedure for each bundle, recording the weights separately for each one. Transport to a drying facility.

Step 14: Perform quality-control checks during sampling.

While in the field, determine the percentage error in the following measurements. We suggest that if the error is greater than ± 5% in each determination, then recalibrate the equipment and reweigh the samples. Resampling may also be necessary.

a. Determine the percentage error in fresh weight of the six-plant ear sample.

Let *ear_fw* = fresh weight (g) of the six-plant ear sample (Step 7)
Let *grain_fw* = fresh weight (g) of the six-plant grain sample (Step 8)
Let *cob_fw* = the fresh weight (g) of the six-plant cob sample (Step 9)
Let *ear_fw_e* = the percentage error in fresh weight of the six-plant ear sample (the quantity to be calculated)

$$ear\_fw\_e = \frac{grain\_fw + cob\_fw - ear\_fw}{ear\_fw} \times 100 \qquad (1)$$

b. For the productive plant bundle only, determine the percentage error in the fresh weight of the six-plant sample — method 1.

Let *plant_fw* = the fresh weight (g) of the six-plant sample (Step 4)
Let *ear_fw* = fresh weight (g) of the six-plant ear sample (Step 7)
Let *stover_fw* = fresh weight (g) of the six-plant stover sample (Step 12)
Let *plant_fw_e1* = the percentage error in the fresh weight of the six-plant sample (the quantity to be calculated)

$$plant\_fw\_e1 = \frac{ear\_fw + stover\_fw - plant\_fw}{plant\_fw} \times 100 \quad (2)$$

c. For the productive plant bundle only, determine the percentage error in the fresh weight of the six-plant sample — method 2.

Let *plant_fw* = the fresh weight (g) of the six-plant sample (Step 4)
Let *grain_fw* = fresh weight (g) of the six-plant grain sample (Step 8)
Let *cob_fw* = the fresh weight (g) of the six-plant cob sample (Step 9)
Let *stover_fw* = fresh weight (g) of the six-plant stover sample (Step 12)
Let *plant_fw_e2* = the percentage error in the fresh weight of the six-plant sample (the quantity to be calculated)

$$plant\_fw\_e2 = \frac{grain\_fw + cob\_fw + stover\_fw - plant\_fw}{plant\_fw} \times 100 \quad (3)$$

Step 15: Dry samples to constant weight.

Transport the following samples to a drying facility: (i) six-plant cob samples from Step 9; (ii) if Step 11 was followed, the six-plant grain moisture sub-samples; (iii) the stover moisture sub-samples from Step 13 (two of these samples if both productive and barren plants were present). The drying facility should be equipped with a forced-air oven calibrated to 70°C and with enough space for the samples to have air space between them. Also place bags and tags of each type into the oven to use for taring scales. After at least 24 hours in the oven, select three samples of each type and record the weights. Repeat with the same samples on each subsequent day. When the weight of each sample does not change from day to day, the samples have been dried to constant weight and drying is complete.

Step 16: Measure the dry weight of the six-plant cob sample.

Weigh the six-plant cob sub-sample (from Step 9) immediately after removing from the oven. Record the weight in grams.

Step 17: Measure the dry weight of the six-plant grain moisture sub-sample (if Step 11 was followed).

Weigh the six-plant grain moisture sub-sample (from Step 11) immediately after removing from the oven. Record the weight in grams.

Step 18: Measure the dry weight of the stover moisture sub-samples.

Weigh the stover moisture sub-samples (from Step 13) immediately after removing them from the oven. Record the weight in grams. If both productive and barren plants were present, there will be two of these sub-samples.

1.2 Calculations

The goal of these calculations is to determine (i) the average (mean) non-grain, aboveground biomass per plant (for barren and productive plants), and (ii) the harvest index (for productive plants only). The harvest index is the unitless ratio of the grain dry matter to the dry matter of the entire aboveground plant biomass. We use this ratio in Module 3. The aboveground biomass, as sampled, is partitioned into stover, grain and cob. Because we dried sub-samples, rather than entire samples, of grain and stover, we determine the dry matter fraction of each of those sub-samples and multiply that fraction by the fresh weights of each of the corresponding larger samples to calculate the dry matter biomass of those larger samples. Because all cobs, rather than a sub-sample, were dried, we simply use the oven-dry weight for the dry matter biomass of the cobs.

Step 1: For productive plants only, calculate the total and mean non-grain, dry matter biomass per productive plant (g/[productive plant]) in the six-plant sample.

Let *plant_num_p* = the number of productive plants determined in 1.1 Procedure Step 2 and used in 1.1 Procedure Step 4
Let *stover_fw_p* = fresh weight (g) of the six-plant stover sample of productive plants (1.1 Procedure Step 12)

Let *stover_sub_fw_p* = fresh weight (g) of the stover moisture sub-sample taken from the productive plant bundle (1.1 Procedure Step 13)
Let *stover_sub_dw_p* = dry weight (g) of the stover moisture sub-sample taken from the productive plant bundle (1.1 Procedure Step 18)
Let *cob_dm_p* = dry weight (g) of the six-plant cob sample taken from the productive plant bundle (1.1 Procedure Step 16)
Let *stover_dm_p* = total non-grain, dry matter biomass (g) of the six-plant sample taken from the productive plant bundle (the quantity to be calculated)
Let *stover_dm_p_mean* = mean non-grain, dry matter biomass per productive plant (g/[productive plant], the quantity to be calculated)

$$stover\_dm\_p = cob\_dm\_p + \frac{stover\_sub\_dw\_p}{stover\_sub\_fw\_p} \times stover\_fw\_p \qquad (4)$$

$$stover\_dm\_p\_mean = \frac{stover\_dm\_p}{plant\_num\_p} \qquad (5)$$

Step 2: For barren plants only, calculate the total and mean dry matter biomass per barren plant (g/[barren plant]) in the six-plant sample.

Let *plant_num_b* = the number of barren plants determined in 1.1 Procedure Step 2 and used in 1.1 Procedure Step 4
Let *stover_fw_b* = fresh weight (g) of the six-plant sample of barren plants (1.1 Procedure Step 4)
Let *stover_sub_fw_b* = fresh weight (g) of the stover moisture sub-sample taken from the barren plant bundle (1.1 Procedure Step 13)
Let *stover_sub_dw_b* = dry weight (g) of the stover moisture sub-sample taken from the barren plant bundle (1.1 Procedure Step 18)
Let *stover_dm_b* = total dry matter biomass (g) of the six-plant sample taken from the barren plant bundle (the quantity to be calculated)
Let *stover_dm_b_mean* = mean dry matter biomass per barren plant (g/[barren plant]), the quantity to be calculated)

$$stover\_dm\_b = \frac{stover\_sub\_dw\_b}{stover\_sub\_fw\_b} \times stover\_fw\_b \qquad (6)$$

$$stover\_dm\_b\_mean = \frac{stover\_dm\_b}{plant\_num\_b} \qquad (7)$$

Step 3: For productive plants only, calculate the dry matter weight (g) of the six-plant grain sample.

Let *grain_fw* = fresh weight (g) of the six-plant grain sample (1.1 Procedure Step 8)
Let *grain_dm* = dry matter weight (g) of the six-plant grain sample (the quantity to be calculated)

If a moisture meter was used (1.1 Procedure Step 10):

Let *grain_moist_m* = six-plant grain sample moisture (%) measured with a moisture meter (1.1 Procedure Step 10)

$$grain\_dm = \frac{100 - grain\_moist\_m}{100} \times grain\_fw \qquad (8)$$

If a grain subsample was taken to determine moisture content (1.1 Procedure Steps 11 and 17):

Let *grain_sub_fw* = fresh weight (g) of the six-plant grain moisture sub-sample (1.1 Procedure Step 11)
Let *grain_sub_dw* = dry weight (g) of the six-plant grain moisture sub-sample (1.1 Procedure Step 17)
Let grain_moist_d = six-plant grain sample moisture (%) measured by oven-drying (a quantity to be calculated)

First calculate *grain_moist_d*:

$$grain\_moist\_d = \frac{grain\_sub\_fw - grain\_sub\_dw}{grain\_sub\_fw} \times 100 \qquad (9)$$

Then calculate *grain_dm:*

$$grain\_dm = \frac{100 - grain\_moist\_d}{100} \times grain\_fw \qquad (10)$$

Step 4: For productive plants only, if 1.1 Procedure Steps 10, 11 and 17 were performed, determine the percentage error of the moisture meter readings, using oven-dried moisture as the standard. This is a quality-control measure.

Let *grain_moist_m* = six-plant grain sample moisture (%) measured with a moisture meter (1.1 Procedure Step 10)
Let grain_moist_d = six-plant grain sample moisture (%) measured by oven-drying (Equation 9)
Let *grain_moist_e* = percentage error (%) of the moisture meter readings (the quantity to be calculated)

$$grain\_moist\_e = \frac{grain\_moist\_m - grain\_moist\_d}{grain\_moist\_d} \times 100 \qquad (11)$$

Step 5: For productive plants only, calculate the harvest index (unitless fraction).

Let *stover_dm_p* = total non-grain, dry matter biomass (g) of the six-plant sample taken from the productive plant bundle (Equation 4)
Let *grain_dm* = dry matter weight (g) of the six-plant grain sample (Equation 8 or 10)
Let *HI* = harvest index (the quantity to be calculated)

$$HI = \frac{grain\_dm}{stover\_dm\_p + grain\_dm} \qquad (12)$$

Module 2: Measurement of grain dry matter yield at harvest

2.1 Procedure

Step 1: Delineate the harvest area and record its dimensions.

We recommend determining the size of the harvest area based on characteristics of individual experimental sites (see SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations). If Module 1 was performed, use the dimensions from 1.1 Procedure Step 1 in that module. Important factors are plant density and yield level. In low-yielding treatments, more plants may be needed to provide sufficient material to be within the calibrated ranges of measurement equipment (refer also to 2.1 Procedure Step 2, below). We recommend testing the harvest dimensions in the treatment that is likely to be the lowest yielding. Start with a given harvest area and go through all the steps in this module to determine whether there is sufficient material for all measurements. If not, incrementally increase the dimensions of the harvest area, running through all the steps each time, to determine the area required. Once appropriate dimensions have been confirmed, record the area (square meters). Use this area consistently across all treatments at a given site.

Step 2: Determine the ear sample size (number of ears required).

Steps 9 and 10 (below) require grain samples of certain quantities. As you determine the harvest area, make sure the number of ears in the harvest area will provide more than enough grain for the measurements in those steps. Start with six ears. Once the number of ears is determined, record it as the ear sample number. Use this number consistently across all treatments at a given site. *Do not use less than six ears*.

Step 3: Confirm that physiological maturity (R6) has occurred.

A maize *plant* is at R6 when 95% or more of the kernels on the ear have formed a black layer. For a *population* of maize plants, R6 is defined as 50% of all plants at this stage of development. Harvest occurs after physiological maturity when the grain has dried to 18% moisture content or less. If a grain moisture meter is available, take samples of grain from the border areas of what are likely to be higher- and lower-yielding treatments and determine whether the grain is at or below 18% for both treatments.

Step 4: Take the ear harvest sample and count barren and productive plants.

Move sequentially from plant to plant through the harvest area. Categorize each plant as barren or productive and keep a running tally of the number of plants in each category. Barren plants either produce no ear or produce an ear with no fully developed grain. Remove all ears (grain and cob) from the productive plants in the harvest area and place them into a large, labeled cloth sack. If Module 1 was used, this will be all the ears except those from previously sampled plants. Record the number of barren and productive plants.

Step 5: Count the number of ears harvested.

Count and record the number of ears harvested and replace them into the large, labeled cloth sack.

As a quality-control measure, ensure the number of ears is equal to or greater than the number of productive plants. The number of ears should not be less than the number of productive plants. If it is, a recount of ears and/or productive plants is required.

Step 6: Measure the fresh weight of the ear harvest sample.

Weigh the ear harvest sample on a tared scale. Record weight in kilograms. Reserve.

Step 7: Measure the fresh weight of the ear sample.

From the ear harvest sample, select the number of representative ears determined in Step 2 (minimum six). Place ears into a large, labeled paper bag and weigh on a tared scale. Record weight in grams.

Step 8: Measure the fresh weight of grain in the ear sample from Step 7.

Using a sheller, remove the grain from the ears. Shell into a plastic bucket, ensuring no grain is lost. Pour all the grain into a large, labeled paper bag and weigh on a tared scale. Record weight in grams. Reserve.

The following steps differ depending on whether or not a calibrated grain moisture meter is available.

If a moisture meter is available:

Step 9: Measure the ear sample grain moisture content.

Mix the ear sample grain thoroughly. Follow the manufacturer's instructions and record grain moisture content (%).

If a moisture meter is not available or as an additional quality-control step:

Step 10: Take a sub-sample of the grain in Step 8 and measure its fresh weight. This sub-sample will be used for moisture determination.

Mix the ear sample grain (from Step 8) thoroughly. Place a medium-sized cloth bag on the scale and tare. Add grain until there is at least 300 g in the bag. Record the exact weight in grams. Transport to a drying facility.

Step 11: Dry the ear sample grain moisture sub-sample to constant weight.

The drying facility should be equipped with a forced-air oven calibrated to 70°C and with enough space for the samples to have air space between them. Also place bags and tags of each type into the oven to use for taring scales. After at least 24 hours in the oven, select three samples and record the weights. Repeat with the same samples on each subsequent day. When the weight of each sample does not change from day to day, the samples have been dried to constant weight and drying is complete.

Step 12: Measure the dry weight of the ear sample grain moisture sub-sample.

Weigh the ear sample grain moisture sub-samples (from Step 11) immediately after removing from the oven. Record weight in grams.

2.2 Calculations

Step 1: Convert harvest area in square meters (m^2) to harvest area in hectares (ha).

Let *harvest_area* = harvest area (m^2) (2.1 Procedure Step 1)
Let *harvest_area_ha* = harvest area (ha, the quantity to be calculated)

$$harvest\_area\_ha = \frac{harvest\_area}{10{,}000} \tag{13}$$

Step 2: From the ear sample, use the ratio of the fresh weight of grain (2.1 Procedure Step 8) to the fresh weight of the ear (2.1 Procedure Step 7) to estimate the fresh weight of grain of all the ears collected in the harvest sample (2.1 Procedure Step 6).

Let *harvest_ear_fw* = fresh weight (kg) of the ear harvest sample (2.1 Procedure Step 6)
Let *ear_fw_h* = fresh weight (g) of the ear sample (2.1 Procedure Step 7)
Let *grain_fw_h* = fresh weight (g) of the ear sample grain (2.1 Procedure Step 8)
Let *harvest_grain_fw* = estimated grain fresh weight (kg) of the ear harvest sample (the quantity to be calculated)

$$harvest\_grain\_fw = \frac{grain\_fw\_h}{ear\_fw\_h} \times harvest\_ear\_fw \tag{14}$$

Step 3: If a grain subsample was taken in 2.1 Procedure Step 10, calculate the moisture content (%) in the grain using the fresh (2.1 Procedure Step 10) and dry (2.1 Procedure Step 12) weights of the subsample.

Let *grain_sub_fw_h* = fresh weight of the grain moisture sub-sample of the ear sample (2.1 Procedure Step 10)
Let *grain_sub_dw_h* = dry weight of the grain moisture sub-sample of the ear sample (2.1 Procedure Step 12)
Let grain_moist_d_h = ear sample grain moisture (%) measured by oven-drying (the quantity to be calculated)

$$grain\_moist\_d\_h = \frac{grain\_sub\_fw\_h - grain\_sub\_dw\_h}{grain\_sub\_fw\_h} \times 100 \tag{15}$$

Step 4: Convert the estimated grain fresh weight (kg) of all the ears in the harvest sample (*harvest_grain_fw*, Equation 14) into estimated grain dry weight (kg). This can be done using the percentage grain moisture determined either by a moisture meter (2.1 Procedure Step 9) or by oven-drying (Equation 15).

Let *harvest_grain_fw* = estimated grain fresh weight (kg) of the ear harvest sample (Equation 14)
Let *harvest_grain_d* = estimated grain dry weight (kg) of the ear harvest sample (the quantity to be calculated)

If grain moisture was determined by a moisture meter (2.1 Procedure Step 9):

Let grain_moist_m_h = ear sample grain moisture (%) measured by a moisture meter (2.1 Procedure Step 9)

$$harvest\_grain\_d = harvest\_grain\_fw \times \frac{100 - grain\_moist\_m\_h}{100} \tag{16}$$

If moisture was determined by oven-drying (2.1 Procedure Steps 10 and 12):

Let grain_moist_d_h = ear sample grain moisture (%) measured by oven-drying (Equation 15)

$$harvest\_grain\_d = harvest\_grain\_fw \times \frac{100 - grain\_moist\_d\_h}{100} \tag{17}$$

Step 5: Express the estimated grain dry weight (kg) of all the ears in the harvest sample on a per hectare basis (kg/ha) by dividing *harvest_grain_d* (Equation 16 or 17) by the *harvest_area_ha* (Equation 13).

Let *harvest_grain_d* = estimated grain dry weight (kg) of the ear harvest sample (Equation 16 or 17)
Let *harvest_area_ha* = harvest area (ha, Equation 13)
Let *gy_dm* = dry matter grain yield (kg/ha, the quantity to be calculated)

If Module 1 was not used prior to Module 2, calculate dry matter grain yield as follows:

$$gy\_dm = \frac{harvest\_grain\_d}{harvest\_area\_ha} \tag{18}$$

If Module 1 was used prior to Module 2, then the grain collected in the six-plant grain sample in Module 1 must be added to the grain collected during harvest:

Let *grain_dm* = dry matter weight (g) of the six-plant grain sample from Module 1 (Equation 8 or 10)
Let *grain_dm_kg* = *grain_dm* expressed in kg (a quantity to be calculated)

First calculate *grain_dm_kg*:

$$grain\_dm\_kg = \frac{grain\_dm}{1000} \tag{19}$$

Then add it to *harvest_grain_d* to calculate *gy_dm*:

$$gy\_dm = \frac{grain\_dm\_kg + harvest\_grain\_d}{harvest\_area\_ha} \tag{20}$$

Step 6: If 2.1 Procedure Steps 9, 10 and 12 were all performed, determine the percentage error of the moisture meter readings, using oven-dried moisture as the standard. This is a quality-control measure.

Let *grain_moist_m_h* = ear sample grain moisture (%) measured by a moisture meter (2.1 Procedure Step 9)
Let grain_moist_d_h = ear sample grain moisture (%) measured by oven-drying (Equation 15)
Let *grain_moist_e_h* = percentage error of the moisture meter readings (the quantity to be calculated)

$$grain\_moist\_e\_h = \frac{grain\_moist\_m\_h - grain\_moist\_d\_h}{grain\_moist\_d\_h} \times 100 \tag{21}$$

Module 3: Calculation of total aboveground dry matter biomass and grain yield at a specified moisture content

3.1 Calculations

This module requires no new measurements. It requires prior completion of the measurements and calculations in Modules 1 and 2.

Step 1: Estimate the aboveground dry matter biomass (kg/ha) of productive plants — method 1 (uses the harvest index).

Let *HI* = harvest index (Equation 12)
Let *gy_dm* = dry matter grain yield (kg/ha) (Equation 18 or 20)
Let *by_dm_p_HI* = aboveground dry matter biomass yield (kg/ha) of productive plants, calculated using harvest index

$$by\_dm\_p\_HI = \frac{gy\_dm}{HI} \tag{22}$$

Step 2: Express the mean non-grain (stover) biomass per productive plant (*stover_dm_p_mean*), calculated in grams in Module 1 (Equation 5) in units of kilograms, and do the same for the mean non-grain (stover) biomass per barren plant (*stover_dm_b_mean*) (Module 1, Equation 7).

For productive plants:

Let *stover_dm_p_mean* = mean non-grain, dry matter biomass per productive plant (g/[productive plant], Equation 5)
Let *stover_dm_p_mean_kg* = mean non-grain, dry matter biomass per productive plant (kg/[productive plant]), the quantity to be calculated:

$$stover\_dm\_p\_mean\_kg = \frac{stover\_dm\_p\_mean}{1000} \tag{23}$$

For barren plants:

Let *stover_dm_b_mean* = mean dry matter biomass per barren plant (g/[barren plant], Equation 7)
Let *stover_dm_b_mean_kg* = mean dry matter biomass per barren plant (kg/[barren plant]), the quantity to be calculated:

$$stover\_dm\_b\_mean\_kg = \frac{stover\_dm\_b\_mean}{1000} \tag{24}$$

Step 3: Estimate the non-grain (stover) biomass (kg/ha) by multiplying the mean, non-grain (stover) dry matter biomass per plant by the number of plants. Do this for both productive and barren plants.

Let *harvest_area_ha* = harvest area in ha (Equation 13)

For productive plants:

Let *stover_dm_p_mean_kg* = mean non-grain, dry matter biomass per productive plant (kg/[productive plant], Equation 23)
Let *plant_num_p_h* = the number of productive plants counted in Module 2 (2.1 Procedure Step 4)
Let *stover_dm_p_h* = total non-grain dry matter biomass yield (kg/ha) of productive plants (the quantity to be calculated)

If Module 1 was not used prior to Module 2:

$$stover\_dm\_p\_h = \frac{stover\_dm\_p\_mean\_kg \text{ x } plant\_num\_p\_h}{harvest\_area\_ha} \tag{25}$$

If Module 1 was used prior to Module 2, the number of productive plants collected in Module 1 (determined in 1.1 Procedure Step 2) must be added to the number of productive plants counted during harvest.

Let *plant_num_p* = the number of productive plants determined in 1.1 Procedure Step 2 and used in 1.1 Procedure Step 4

$$stover\_dm\_p\_h = \frac{stover\_dm\_p\_mean\_kg \text{ x } (plant\_num\_p\_h + plant\_num\_p)}{harvest\_area\_ha} \tag{26}$$

For barren plants:

Let *stover_dm_b_mean_kg* = mean dry matter biomass per barren plant (kg/[barren plant], Equation 24)
Let *plant_num_b_h* = the number of barren plants counted in Module 2 (2.1 Procedure Step 4)

Let *stover_dm_b_h* = total dry matter biomass yield (kg/ha) of barren plants (the quantity to be calculated)

If Module 1 was not used prior to Module 2:

$$stover\_dm\_b\_h = \frac{stover\_dm\_b\_mean\_kg \times plant\_num\_b\_h}{harvest\_area\_ha} \qquad (27)$$

If Module 1 was used prior to Module 2, the number of barren plants collected in Module 1 (determined in 1.1 Procedure Step 2) must be added to the number of barren plants counted during harvest.

Let *plant_num_b* = the number of barren plants determined in 1.1 Procedure Step 2 and used in 1.1 Procedure Step 4

$$stover\_dm\_b\_h = \frac{stover\_dm\_b\_mean\_kg \times (plant\_num\_b\_h + plant\_num\_b)}{harvest\_area\_ha} \qquad (28)$$

Step 4: Estimate the aboveground dry matter biomass (kg/ha) of productive plants — method 2 (uses dry matter summation).

Let *stover_dm_p_h* = total non-grain dry matter biomass yield (kg/ha) of productive plants (Equation 25 or 26)
Let *gy_dm* = dry matter grain yield (kg/ha, Equation 18 or 20)
Let *by_dm_p_s* = aboveground dry matter biomass yield (kg/ha) of productive plants, calculated by summation

$$by\_dm\_p\_s = gy\_dm + stover\_dm\_p\_h \qquad (29)$$

Step 5: Determine the percentage error of the aboveground dry matter biomass (kg/ha) estimates for productive plants. This is a quality-control measure. We use the calculation based on the harvest index as the standard for comparison.

Let *by_dm_p_HI* = aboveground dry matter biomass yield (kg/ha) of productive plants, calculated using harvest index (Equation 22)
Let *by_dm_p_s* = aboveground dry matter biomass yield (kg/ha) of productive plants, calculated by summation (Equation 29)
Let *by_dm_p_e* = percentage error of the aboveground dry matter biomass estimates for productive plants (the quantity calculated)

$$by\_dm\_p\_e = \frac{by\_dm\_p\_s - by\_dm\_p\_HI}{by\_dm\_p\_HI} \times 100 \qquad (30)$$

Step 6: Estimate the total aboveground dry matter biomass (kg/ha) of all plants (productive and barren).

Let *by_dm_p_HI* = aboveground dry matter biomass yield (kg/ha) of productive plants, estimated using harvest index (Equation 22)
Let *by_dm_p_s* = aboveground dry matter biomass yield (kg/ha) of productive plants, estimated by summation (Equation 29)
Let *stover_dm_b_h* = total dry matter biomass yield (kg/ha) of barren plants (Equation 27 or 28)
Let *by_dm_HI* = total aboveground dry matter biomass (kg/ha) of all plants, using HI for productive plants (the quantity to be calculated)
Let *by_dm_s* = total aboveground dry matter biomass (kg/ha) of all plants, using summation for productive plants (the quantity to be calculated)

$$by\_dm\_HI = stover\_dm\_b\_h + by\_dm\_p\_HI \qquad (31)$$

$$by\_dm\_s = stover\_dm\_b\_h + by\_dm\_p\_s \qquad (32)$$

Step 7: Determine the percentage error of the total aboveground dry matter biomass (kg/ha) of all plants. This is a quality-control measure. We use the calculation based on the harvest index as the standard for comparison.

Let *by_dm_HI* = total aboveground dry matter biomass (kg/ha) of all plants, using HI for productive plants (Equation 31)
Let *by_dm_s* = total aboveground dry matter biomass (kg/ha) of all plants, using summation for productive plants (Equation 32)
Let *by_dm_e* = percentage error of the total aboveground dry matter biomass calculations for all plants (the quantity to be calculated)

$$by\_dm\_e = \frac{by\_dm\_s - by\_dm\_HI}{by\_dm\_HI} \times 100 \qquad (33)$$

Step 8: Calculate grain yield (kg/ha) at a specified grain moisture content (e.g. 15.5% moisture).

Let *gy_dm* = dry matter grain yield (kg/ha, Equation 18 or 20)
Let *grain_moist_s* = specified grain moisture content (%)
Let *grain_dm_s* = dry matter content corresponding to the specified grain moisture content (a quantity to be calculated)
Let *gy_sm* = grain yield (kg/ha) at a specified moisture content (quantity to be calculated)

First calculate *grain_dm_s*, a unitless quantity:

$$grain\_dm\_s = \frac{100 - grain\_moist\_s}{100} \qquad (34)$$

Next, divide dry matter grain yield by the dry matter content corresponding to the specified grain moisture content:

$$gy\_sm = \frac{\mathrm{gy\_dm}}{grain\_dm\_s} \qquad (35)$$

Contributors

T. Scott Murrell and P. Chivenge (African Plant Nutrition Institute [APNI])

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Suggested citation: Murrell TS and Chivenge P. 2022. Measurement of maize grain yield and aboveground biomass at maturity by crop cut at plot level, v1. Standard Operating Procedure 005. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d'Ivoire.

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Measurement of potato tuber yield at maturity by crop cut at plot level

SOP ID: 006

Version: 1

Crop: Potato (*Solanum tuberosum*)

Relevant KPIs: Productivity — yield; Resource use efficiency — nutrient use efficiency

R&D stage (example of activities):

- Discovery stage (yield decomposition)
- Proof-of-concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Pilot stage (on-farm participatory trials, randomized control trial)
- Scaling stage (panel studies, ex-post impact assessment)

Module 1: Measurement of tuber yield

1.1 Required equipment/materials

- Measuring tape
- Four pegs
- String or rope
- Paper or cloth or woven bags or sacks
- Sickle
- Digging fork or hoe
- Digital weighing balance
- Data recording tools/sheet
- Drying oven
- Kitchen knife
- Cutting board

1.2 Procedure

Step 1: Identify the right harvest time. Harvesting should be done when the crop is well mature, at complete death of the foliage, and when the tubers' skin is firm and cannot be removed by lightly rubbing the tubers with fingers. It is recommended you dehaulm plants when the foliage begins to turn yellow, and harvest 10–15 days later. Dehaulming is removing or destroying the shoots above the soil ahead of the complete maturity of the plant. It is recommended that you apply superficial irrigation 2 to 3 days before harvesting the tubers to facilitate digging them up.

Step 2: Select the net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

Step 3: Locate and mark the net harvest area by placing four pegs — one at each corner. Only tubers that are inside the delineated area should be harvested.

Step 4: Count the number of plants within the net harvest area.

Step 5: Dig up all tubers in the net harvest area and leave them on the ground to dry until the soil caked on the tubers dries and falls off (maximum 2 hours).

Step 6: Count the number of tubers. Optionally disaggregate the tubers as (i) small tubers (diameter < 3 cm); (ii) large, diseased/damaged tubers (diameter ≥ 3 cm and severe to extremely severe symptoms of diseases/pests); and (iii) large, marketable tubers (diameter ≥ 3 cm and no to mild symptoms of diseases/pests).

Step 7: Measure the fresh weight of the tubers. Optionally disaggregate the tubers as in Step 6.

Step 8: Take one or more (sub-) samples of the tubers (all tubers or disaggregated by size and disease damage as in Step 6) of about 100–200 g per (sub-) sample for dry matter assessment and record the fresh weight. Place them in bags or sacks with proper labels (barcode, or site, date, treatment, replication, plot number, etc.). We recommend you sample at least 1% of the total tuber weight harvested in the net plot to make sure the sample is representative. If 1% of the total harvested tuber weight is more than 200 g, divide the sample into several sub-samples and place them in different bags for oven-drying.

Step 9: Transport samples to a research station or any other place where samples can be properly processed, dried and stored.

Step 10: Cut the tuber samples into small pieces and oven-dry (with forced air circulation) at 105˚C for 72 hours or until constant weight. Keep some space between samples in the oven to allow a flow of air inside the oven and avoid fermentation of the samples. Measure the dry weight of the samples.

1.3 Calculation

Step 1: Calculate the fresh tuber yield (kg/ha) using formula (1).

$$\text{Fresh tuber yield (kg/ha)} = \frac{\text{Fresh tuber weight of the net harvest area (g)}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (1)$$

Where the division by 1000 is the conversion of grams to kg; and the multiplication by 10,000 is the conversion from m^2 to ha.

You *may* also calculate fresh *marketable* tuber yield (kg/ha) using the fresh weight of the marketable tubers (diameter > 3 cm and no to mild symptoms of diseases/pests) in the net harvest area.

Step 2: Calculate the dry matter content of the fresh tubers (%) using formula (2).

$$\text{Dry matter content of the fresh tubers (\%)} = \frac{\text{Dry weight of the sample (g)}}{\text{Fresh weight of the sample (g)}} \times 100 \qquad (2)$$

Step 3: Calculate the dry tuber yield (kg/ha) using formula (3).

$$\text{Dry tuber yield (kg/ha)} = \left(\frac{\text{Fresh tuber weight of net harvest area (g)} \times \left[\frac{\text{Dry matter content of fresh tubers (\%)}}{100} \right]}{1000} \right) \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (3)$$

Contributors

Elke Vandamme, Javier Rinza, David Ramirez and Johan Ninyana (International Potato Center [CIP])

Suggested citation: Vandamme E, Rinza J, Ramirez D and Ninyana J. 2022. Measurement of potato tuber yield at maturity by crop cut at plot level, v1. Standard Operating Procedure 006. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d’Ivoire.

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Measurement of rice grain yield and aboveground biomass at maturity for crop cut at plot level

SOP ID: 007

Version: 1

Crop: Rice (*Oryza* spp.)

Relevant KPI: Productivity — yield; Resource use efficiency — nutrient use efficiency

R&D stage (example of activities):

- Discovery stage (yield decomposition)
- Proof of concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Pilot stage (on-farm participatory trials, randomized control trials)
- Scaling stage (panel studies, ex-post impact assessment)

1. Module 1: Measurement of grain yield

1.1 Required equipment/materials

- Measuring tape
- Four pegs
- String or rope
- Cloth or woven poly sacks
- Sickle
- Digital weighing balance
- Grain moisture meter
- Data recording tools/sheet

1.2 Procedure

Step 1: Identify right harvest time: harvesting should be done when grain moisture content is 18–23%, or when 80–85% of the grains are ripened (turned to straw color).

Step 2: Select net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

Step 3: Locate and mark the net harvest area by placing four pegs — one at each corner. When marking net harvest area, take into account crop establishment method. For example, in the case of uniform line seeding/transplanting, pegs should be placed centrally between rows on all sides. If plants are in random geometry (e.g. randomly broadcasted or transplanted), only panicles that fall inside the marked area should be harvested.

Step 4: Cut all panicles within the net harvest area and place them in the sacks with proper labels (barcode, or details of site, date, treatment, replication, plot number, etc.).

Step 5: Transport samples to research station or any other place where they can be properly processed, dried and stored before weighing.

Step 6: Thresh panicles manually or mechanically to separate the grain and clean to remove chaff and unfilled grains.

Step 7: If grain moisture content is more than 16% before measuring weight, dry grains to reduce the moisture content below 16%. If harvest samples are to be used for grain quality assessment, dry the samples under the sun to a moisture content of around 16%, then continue drying under shade to 14% before weighing. In areas where the temperature is high and humidity is low (e.g. arid and semi-arid agro-ecological zones), the samples should be dried under shade only to avoid rapid moisture loss. If the samples are not used for grain quality assessment, they can be dried under the sun to 14% moisture content.

Step 8: Measure grain weight (grams) from net harvest area using a digital balance and immediately measure the grain moisture content using a grain moisture meter. Ensure the balance is placed on a well-leveled surface. Also make sure the grain moisture meter is calibrated for rice. If harvested grains are used for grain quality assessment, take a sub-sample and put it in a ziplock bag or other container before lab analysis.

1.3 Calculation

Step 1: Convert the grain weight (net harvest area) to 14% moisture content using formula (1).

$$\text{Grain weight at 14\% moisture content} = \text{Grain weight (g)} \times \frac{[100 - \text{Grain moisture content (\%)}]}{86} \qquad (1)$$

Step 2: Calculate grain yield in kg per hectare (at 14% moisture content) using formula (2).

$$\begin{array}{l}\text{Grain yield (kg/ha) at} \\ \text{14\% moisture content}\end{array} = \frac{\text{Grain yield (g) net harvest area at 14\% moisture}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (2)$$

Where the division by 1000 is the conversion of grams to kg; and the multiplication by 10,000 is the conversion from m^2 to ha.

2. Module 2: Measurement of milled and head rice yields

2.1 Required equipment/materials

- Aluminum bags
- Polyethylene bag
- Carton
- Container
- Rice test mill, e.g. Rice Test Mill PAZ-1 DTA (ZaccariaUSA, TX, USA)
- Digital balance
- Rotary test rice grader.

2.2 Procedure

Step 1: After measuring filled grain yield, take 100 g of filled grain for milling. If samples need to be sent to a grain quality lab that is not near your location or samples need to be stored for a long time, put samples in aluminum bags to prevent moisture re-absorption and insect attack. All samples should be put in polyethylene bags prior to putting in cartons.

Step 2: Milling is done using a rice test mill such as Rice Test Mill PAZ-1 DTA (ZaccariaUSA, TX, USA). For this equipment, paddy rice samples are poured into the hopper, which has been adjusted to allow de-husking to be completed in 15 seconds and polishing in 60 seconds, making a total of 75 seconds.

Step 3: Determine milled rice weight using a digital balance (for calculating milling recovery, %).

Step 4: Milled rice is separated into whole and broken grains using a rotary test rice grader.

Step 5: Determine head rice weight using a digital balance (for calculating head rice yield, %).

Step 6: The whole grain samples can be used for further analysis such as grain dimensions, chalkiness index, amylose content, protein content, cooking quality and cooked grain texture. The samples should be well stored as indicated above before further analyses (Step 1).

2.3 Calculations

Step 1:

$$\text{Milled rice recovery (\%)} = \frac{\text{Weight of milled rice (g)}}{\text{Weight of 100 filled grains (g)}} \times 100 \quad (3)$$

Step 2:

$$\text{Milled rice yield (kg/ha)} = \frac{\text{Filled grain yield (kg/ha)} \times \text{Milled rice recovery (\%)}}{100} \quad (4)$$

Step 3:

$$\text{Head rice yield (\%)} = \frac{\text{Weight of whole grains (g)}}{\text{Weight of 100 filled grains (g)}} \times 100 \quad (5)$$

3. Module 3: Measurement of aboveground biomass

3.1 Required equipment/materials

- Measuring tape
- Four pegs
- String or rope
- Cloth or woven poly sacks
- Sickle
- Paper bag
- Ziplock bag
- Digital weighing balance
- Oven
- Data recording tools/sheet.

3.2 Procedure

Step 1: Identify the physiological maturity stage in the field. Physiological maturity is the point at which grain filling ends and it typically occurs several days before harvestable maturity. Physiological maturity is visually identified when grains on the lower portion of secondary and tertiary panicles reach the hard dough stage and begin to lose their green color.

Step 2: Select net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

Step 3: Locate and mark the net harvest area by placing four pegs — one at each corner. When marking net harvest area, take into account the crop establishment method. For example, in the case of line seeding/transplanting, pegs should be placed *between* rows on each side (not close up to a row so as to include one too many rows in the sample). If plants are in random geometry (e.g. randomly broadcasted or transplanted), only plants/stems inside the delineated area should be harvested.

Step 4: Cut all plants from the net harvest area at the ground surface. Make sure that no rice leaves or stems (including dead tillers) are lost. Remove other plants (weeds) and soil debris from harvested plants. Carefully place the harvested sample in large woven poly sacks with panicles facing downward into the sacks. The bag should be pre-labeled (barcode, or details of site, farm number, year, treatment, date of sampling, plot number, etc.). If there is any soil on the stems, carefully rinse adhering soil off with clean water.

Step 5: Transport samples to a research station or any other place where they can be properly processed, dried and stored before weighing.

Step 6: Thresh the harvested sample manually or mechanically to separate grains and straw as early as possible to avoid deterioration.

Step 7: Separate harvested samples into filled grains, unfilled grains and straw (peduncle and rachis are part of straw [stems and leaves]) and place them in separate bags that have been properly labeled. Record the fresh weight of filled grains (g), unfilled grains (g) and straw (g) from the net harvested area using a digital balance.

If samples are small, all can be put into the oven prior to measuring dry weight. If grain and straw sample sizes are large (more than 2 kg), take a sub-sample of 300–400 g (depending on sample size) for both grain and straw samples and put into separate paper bags and label them properly. Record the fresh weight (g) of both grain and straw sub-samples using a digital balance.

Step 8: Oven-dry the samples of filled grains, unfilled grains and straw at 70°C for 3 days or until the weight is stable. Record the oven-dried sub-sample weight of filled grains, unfilled grains and straw (g) immediately after taking them out of the oven (do not let the samples rehydrate!).

Avoid overloading the oven with samples because good air circulation is needed for rapid and even drying. Record the final oven-dry weight of each sub-sample (g).

Step 9: Grain and straw samples for quality analysis: take a sub-sample of about 20–30 g of oven-dried filled grains and place it in a ziplock bag, and take a sub-sample of around 200 g of straw and place it in a paper bag. Label both properly. These samples will be used for further laboratory analysis.

3.3 Calculations

Step 1: Calculation of dry weight of filled and unfilled grains:

$$\text{Dry weight of filled grains (kg/ha)} = \frac{\text{Dry weight of filled grains (g)}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \tag{6}$$

$$\text{Dry weight of unfilled grains (kg/ha)} = \frac{\text{Dry weight of unfilled grains (g)}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \tag{7}$$

For large sample size:

$$\text{Dry weight of filled grain (kg/ha)} = \frac{\text{Total fresh filled grain weight (g)} \times \left[\dfrac{\text{Dry weight of grain sub-sample (g)}}{\text{Fresh weight of grain sub-sample (g)}}\right]}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \tag{8}$$

Step 2: Calculation of dry weight of straw

$$\text{Dry weight of straw (kg/ha)} = \frac{\text{Total straw weight (g)} \times \left[\dfrac{\text{Dry weight of straw sub-sample (g)}}{\text{Fresh weight of straw sub-sample (g)}}\right]}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \tag{9}$$

Step 3: Calculation of total aboveground biomass (oven-dried weight) and harvest index

$$\text{Total aboveground biomass (kg/ha)} = \text{Dry weight of filled grains (kg/ha)} + \text{Dry weight of unfilled grains (kg/ha)} + \text{Dry weight of straw (kg/ha)} \tag{10}$$

$$\text{Harvest index} = \frac{\text{Dry weight of filled grains (kg/ha)}}{\text{Total aboveground biomass (kg/ha)}} \tag{11}$$

Step 4: Compare grain yield measured in module 1 with filled grain weight in module 3.

Typically, grain yield estimated from a smaller area (module 3) tends to be greater than grain yield from the large grain yield harvest area, but they should be strongly correlated. If they are widely different, aboveground biomass can be adjusted as per equation (12).

$$\text{Adjusted aboveground biomass (kg/ha)} = \frac{\text{Filled grain yield at 14\% moisture content (module 1) (kg/ha)}}{\text{Filled grain yield at 14\% moisture content (module 3) (kg/ha)}} \times \text{Aboveground biomass (module 3) (kg/ha)} \quad (12)$$

Contributors

Kazuki Saito, Sali Atanga Ndindeng (Africa Rice Center [AfricaRice]), Mina Devkota (International Center for Agricultural Research in the Dry Areas [ICARDA]), Achim Dobermann (International Fertilizer Association [IFA])

Suggested citation: Saito K, Ndindeng SA, Devkota M and Dobermann A. 2022. Measurement of rice grain yield and aboveground biomass at maturity for crop cut at plot level, v1. Standard Operating Procedure 007. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d'Ivoire.

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Measurement of sorghum grain yield and aboveground biomass at maturity by crop cut at plot level

SOP ID: 008

Version: 1

Crop: Sorghum (*Sorghum bicolor*)

Relevant KPIs: Productivity — yield; Resource use efficiency — nutrient use efficiency

R&D stage (example of activities):

- Discovery stage (yield decomposition)
- Proof-of-concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Pilot stage (on-farm participatory trials, randomized control trial)
- Scaling stage (panel studies, ex-post impact assessment)

Module 1: Measurement of grain yield

1.1 Required equipment/materials

- Measuring tape
- Pegs
- String or rope
- Cloth or woven polyethylene sacks
- Sickle bar headers
- Digital weighing balance
- Grain moisture meter
- Data recording tools/sheet

1.2 Procedure for the taking sample from the field

Step 1: Identify the right harvest time. Sorghum pollinates first at the top of the head and progresses steadily downward to the base of the head (or flower cluster) in 4 to 7 days. Hence, seeds at the top will mature before those at the bottom of the head. Sorghum is considered mature when a black spot appears at the point where the seed attaches to the plant. It is ready to harvest when (i) grain moisture content is less than 28%, and (ii) the heads are yellow and the grains hard.

Step 2: Select net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

Step 3: Locate and mark the net harvest area by placing four pegs — one at each corner. Net harvest area should be representative of the entire plot and should not include border rows to avoid the border effect. When marking the net harvest area, take into account the crop establishment method. For example, if line-seeded, pegs should be placed centrally between two rows on both sides (Fig. 1 left). If plants are in random geometry (e.g. randomly broadcasted), only heads from stems that fall inside the delineated area should be harvested.

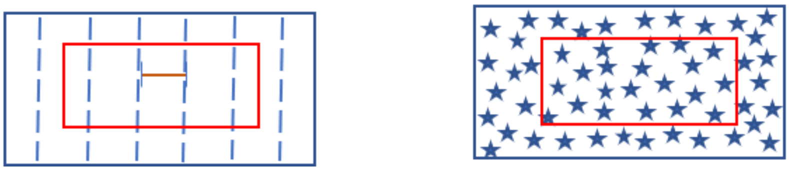

Figure 1. Illustration of crops planted in line (i.e. rows; left) and random (right) geometry and area demarcation for harvesting both planting systems

Only the plants that fall inside the marked area (red box) need to be harvested.

Step 4: Cut all grain heads within the net harvest area. For harvesting grain, raise the sickle bar header high enough to harvest only the grain heads with a minimum of leaves and stalks. Place harvested heads in sacks with proper labels (barcode, or location, harvesting date, treatment, replication, plot number, etc.).

Step 5: Transport the harvested grain heads to a research station or any other place where samples can be properly processed, dried and stored before measuring grain weight.

Step 6: After sun-drying**,** thresh manually or mechanically to separate grains from heads and clean to remove the chaff.

Step 7: Measure grain weight (grams) from the net harvest area using a digital balance and then immediately measure the grain moisture content using a grain moisture meter.* Make sure that the balance is placed on a well-leveled surface. Also, make sure the grain moisture meter is calibrated for sorghum.

> *Note:* * If there is no grain moisture meter available, grain moisture content can be determined for a representative sub-sample by weighing the sample fresh (at the same time as the total grain weight is determined) and drying it to constant weight either in an oven (typically at 75°C) or by sun and air. Then dry-weigh the sub-sample. The moisture content of the total grain weight is calculated by dividing the difference between fresh and dry weights of the sub-sample by the fresh weight of the sub-sample.

> *Note:* If harvested grains are used for grain quality assessment, take a sub-sample of around 300 g and put it in a ziplock bag or container ready for lab analysis.

1.3 Calculation

Step 1: Convert the grain weight (net harvest area) to 12% moisture content using formula (1).

$$\text{Grain weight at 12\% moisture content (g)} = \text{Grain weight (g)} \times \frac{100 - \text{Grain moisture content (\%)}}{88} \qquad (1)$$

Step 2: Calculate grain yield (kg/ha) (at 12% moisture content) using formula (2).

$$\text{Grain yield (kg/ha) at 12\% moisture content} = \frac{\text{Grain yield (g) of net harvest area at 12\% moisture}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (2)$$

Where the division by 1000 is the conversion of grams to kg; and the multiplication by 10,000 is the conversion from m^2 to ha.

Module 2: Measurement of aboveground biomass

2.1 Required equipment/material

- Measuring tape
- Four pegs
- String or rope
- Cloth or woven polyethylene sacks
- Sickle
- Paper bag
- Ziplock bag
- Digital weighing balance
- Drying oven
- Data recording tools/sheet

2.2 Procedure

Step 1: Identify the physiological maturity stage in the field. Sorghum is considered mature when a black spot appears at the point where the seed attaches to the plant.

Step 2: Select net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

Step 3: Locate and mark the net harvest area by placing four pegs — one in each corner. When marking the net harvest area, take into account the crop establishment method. For example, if line-seeded, pegs should be placed centrally between rows on both sides. If plants are in random geometry (e.g. randomly broadcasted), only stems that fall inside the delineated area should be harvested.

Step 4: Harvest all plants from the net harvest area: to minimize the grain loss, first harvest grain heads using the sickle bar headers and place them in a large woven polyethylene sack and label them properly. After removing grain heads, cut stems at ground level and make sure that no dried leaves or stems (including dead tillers) are left in the harvest area.

Step 5: Chop each plant into 3–4 pieces (bottom, middle and top parts), bundle them together and record the total fresh weight of biomass (g) using a digital weighing balance. Immediately take a representative sub-sample of about 300 g (depending on the total biomass weight) to measure dry biomass. Measure the exact fresh weight of the biomass sub-sample (g) using a digital weighing balance and put the sub-sample in a paper/cotton cloth bag. The bag should be pre-labeled (barcode, or location, farm number, year, treatment, date of sampling, plot number, etc.).

Note: For representative sub-sampling for biomass, take three pieces each from the bottom, middle and top parts of the plant, and chop them into small pieces to facilitate proper drying.

Step 6: Transport samples (grain heads and biomass sub-sample) to a research station or any other place where samples can be properly processed, dried and stored before further processing.

Step 7: Thresh the harvested grain heads manually or mechanically to separate grains from heads.

Step 8: Separate harvested grain heads into grains and chaff and place them in separate bags that have been properly labeled. Record the total fresh weight of grains (g) and chaff (g) from the net harvested area using a digital balance.

If the samples are small, all samples can be put into the oven for measuring dry weight. If grain sample size is large (more than 1 kg), take a grain sub-sample of 200 g (depending on sample size) and put it into a paper bag properly labeled. Record the weight of sub-samples using a digital balance — this is the grain sub-sample fresh weight (g).

Step 9: Oven-dry the sub-samples of grains, biomass and chaff at 70°C for 3 days or until reaching a stable weight. Record the oven-dried sub-sample weight of grains (g), biomass (g) and chaff (g) immediately after taking out from the oven (do not let the samples rehydrate!).

Note: Avoid over-packing samples in the oven because good air circulation is needed for rapid and even drying.

Step 10: Grain and biomass samples for quality analysis: take a sub-sample of 20–30 g of the oven-dried grains and place them in a ziplock bag properly labeled, and take a sub-sample of 20–30 g of the oven-dried biomass and place it in a paper bag properly labeled. These samples can be used for further laboratory analysis.

2.3 Calculation

Step 1: Calculation of grain and chaff dry weight

For small samples

$$\text{Dry weight of grain (kg/ha)} = \frac{\text{Dry weight of grains (g)}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \quad (3)$$

$$\text{Dry weight of chaff (kg/ha)} = \frac{\text{Dry weight of chaff (g)}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \quad (4)$$

For large samples

$$\text{Dry weight of grain (kg/ha)} = \left[\frac{\text{Total fresh grain weight (g)} \times \dfrac{\text{Dry weight of grain sub-sample (g)}}{\text{Fresh weight of grain sub-sample (g)}}}{1000} \right] \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \quad (5)$$

$$\text{Dry weight of chaff (kg/ha)} = \frac{\text{Dry weight of chaff (g)}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \quad (6)$$

Step 2: Calculation of dry weight of biomass

$$\text{Dry weight of biomass (kg/ha)} = \left[\frac{\text{Total fresh biomass weight (g)} \times \dfrac{\text{Dry weight of biomass sub-sample (g)}}{\text{Fresh weight of biomass sub-sample (g)}}}{1000} \right] \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \quad (7)$$

Step 3: Calculation of total aboveground biomass (oven-dried weight) and harvest index

$$\text{Total aboveground biomass (kg/ha)} = \text{Dry weight of grains (kg/ha)} + \text{Dry weight of chaff (kg/ha)} + \text{Dry weight of biomass (kg/ha)} \quad (8)$$

$$\text{Harvest index} = \frac{\text{Dry weight of grains (kg/ha)}}{\text{Total aboveground biomass (kg/ha)}} \quad (9)$$

Contributor

Mina Devkota (International Center for Agricultural Research in the Dry Areas [ICARDA])

Suggested citation: Devkota M. 2022. Measurement of sorghum grain yield and aboveground biomass at maturity by crop cut at plot level, v1. Standard Operating Procedure 008. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d'Ivoire.

This work was financially supported by the Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

Measurement of wheat grain yield and aboveground biomass at maturity for crop cut at plot level

SOP ID: 009

Version: 1

Crop: Bread wheat (*Triticum aestivum* subsp. *aestivum*) and Durum wheat (*Triticum turgidum* subsp. *durum*)

Relevant KPI: Productivity — yield; Resource use efficiency — nutrient use efficiency

R&D stage (example of activities):

- Discovery stage (yield decomposition)
- Proof-of-concept stage (testing of improved agronomic practices in on-station and/or on-farm trials)
- Pilot stage (on-farm participatory trials, randomized control trial)
- Scaling stage (panel studies, ex-post impact assessment)

Module 1: Measurement of grain yield

1.1 Required equipment/materials

- Measuring tape
- Four pegs (optional)
- String or rope
- Cloth or woven polyethylene sacks
- Labels
- Marker
- Sickle
- Digital weighing balance
- Grain moisture meter
- Data recording tools/sheet
- Plot combine harvester (optional)

1.2 Procedure for taking sample

Step 1: Identify right harvest time. Wheat is considered ready to harvest when grain moisture content is below 15% or spikelets are yellowing.

Step 2: Select net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

For manual harvesting

Step 3: Locate and mark the net harvest area by placing four pegs — one at each corner. The dimensions of the harvest area should be representative for the field. When marking net harvest area, take into account crop establishment method. For example, if line-seeded, pegs should be placed centrally between rows on both sides (Fig. 1 left). If plants are in random geometry (e.g. randomly broadcasted), only spikes from stems that fall inside the delineated area should be harvested.

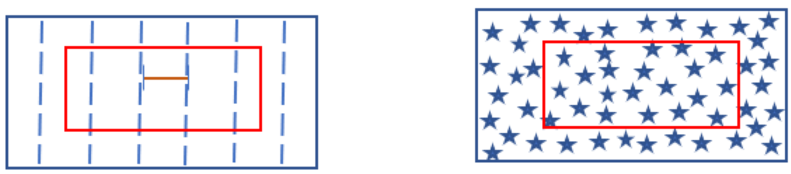

Figure 1. Sampling areas (red rectangles) for wheat planted in rows (left) and random geometry (right)

Figure 1 illustrates wheat seeded in line and random geometry, with the area marked for net harvesting in each. Only plants that fall *inside* the marked area (inside the red box) need to be harvested. The sampling (net harvest) area is measured and marked out in the field accordingly.

Step 4: Record net harvest area (m^2): width [m] and length [m] as explained above.

Step 5: Cut all spikes within the net harvest area and place them in sacks with proper labels (barcode, or details of location, harvesting date, treatment, replication, plot number, etc.).

Step 6: Transport the harvested spikes to a research station or any other place where samples can be properly processed, dried and stored before measuring grain weight.

Step 7: Thresh the spikes manually or mechanically to separate grains from spikes, and clean the grain to remove chaff (i.e. winnow).

Step 8: Measure grain weight (g) from net harvest area using a digital balance and immediately measure the grain moisture content using a grain moisture meter. Make sure that the balance is placed on a well-leveled surface. Also, make sure the grain moisture meter is calibrated for wheat.

> *Note:* The pegs to mark harvest area are especially important when seed was broadcasted. In other sowing arrangements (e.g. line sowing on the flat or on elevated beds) or when the whole plot is harvested in small plot experiments), the pegs can often be omitted, as long as the harvested area is clear.

When using a plot combine harvester

Step 3: After determining the net harvest area (the dimensions of the harvest area should be representative for the field) and marking it out, remove the surrounding border area manually.

Step 4: Record width (m) and length (m) of net harvest area. Consider the crop establishment method as described above.

Step 5: Use a properly labeled grain collection bag to collect grain and run the plot combine harvester in the net harvest area. Make sure that grain loss during harvesting is minimal.

Step 6: If necessary, clean the harvested grain, then weigh the total grain (g) using a digital balance and record the results.

Step 7: Immediately measure the grain moisture content (%) using a grain moisture meter.*

> *Note:* * If there is no grain moisture meter available, grain moisture content can be determined for a representative sub-sample by weighing the sample fresh (at the same time as the total grain weight is determined) and drying it to constant weight either in an oven (typically at 75°C) or by sun and air. Then dry-weigh the sub-sample. The moisture content of the total grain weight is calculated by dividing the difference between fresh and dry weights of the sub-sample by the fresh weight of the sub-sample.

> *Note:* If harvested grains are used for grain quality assessment, take a sub-sample and put it in a paper bag, ziplock bag or container ready for lab analysis.

1.3 Calculation

Step 1: Calculate the net harvest area in m^2

$$\text{Area (m}^2\text{)} = \text{Width (m)} \times \text{Length (m)} \tag{1}$$

Step 2: Convert the grain weight (net harvest area) to 12% moisture content using formula (2).

$$\text{Grain weight at 12\% moisture content (g)} = \text{Grain weight (g)} \times \frac{100 - \text{grain moisture content (\%)}}{88} \tag{2}$$

Step 3: Calculate grain yield (kg/ha) at 12% moisture content using formula (3).

$$\text{Grain yield (kg/ha) at 12\% moisture content} = \frac{\text{Grain weight at 12\% moisture (g)}}{1000} \times \frac{10{,}000}{\text{Area (m}^2\text{)}} \tag{3}$$

The division by 1000 is the conversion of grams to kg; and the multiplication by 10,000 is the conversion from m^2 to ha.

Module 2: Measurement of aboveground biomass

2.1 Required equipment/materials

- Measuring tape
- Four pegs
- String or rope
- Cloth or woven polyethylene sacks
- Sickle
- Paper bag
- Ziplock bag
- Digital weighing balance
- Drying oven
- Data recording tools/sheet

2.2 Procedure

Step 1: Identify the physiological maturity stage in the field. Physiological maturity is the point at which grain reaches hard dough stage, i.e. when spikes completely lose their green color; it typically occurs a few days before harvestable maturity.

Step 2: Select net harvest area (m^2) following SOP001 Determination of the minimum number of plants and the minimum area to be harvested for correct crop yield determinations.

Step 3: Locate and mark the net harvest area by placing four pegs — one at each corner. When marking net harvest area, take into account crop establishment method. For example, if line-seeded, pegs should be placed centrally between rows on both sides. If plants are in random geometry (e.g. randomly broadcasted), only stems that fall *inside* the delineated area should be harvested. Record width and length of the net harvest area.

Step 4: Cut all plants from the net harvest area at ground level. Make sure to collect all aboveground biomass (including dead tillers). Remove other plants (weeds) and soil debris from harvested plants. Carefully place the harvested sample in large woven polyethylene sacks, with the spikes pointing downwards into the sacks. The bags should be pre-labeled (barcode, or details of location, farm number, year, treatment, date of sampling, plot number, etc.).

Step 5: Transport samples to a research station or any other place where they can be properly processed, dried and stored before weighing.

Step 6: Thresh the harvested sample manually or mechanically to separate grains and straw as soon as possible.

Step 7: Separate harvested samples into grains and straw, and place them into separate bags that have been properly labeled. Record the fresh weight of grains (g) and straw (g) from the net harvested area using a digital balance.

If the samples are small, whole samples can be put into the oven for measuring dry weight. If grain and straw samples are large (more than 1 kg), take a sub-sample of 100–200 g (depending on sample size) of each of grain and straw and put these into separate paper bags, properly labelled. Measure the fresh weight (g) of sub-samples using a digital balance for both grain and straw sub-samples.

Step 8: Oven-dry the samples of grains and straw at 75°C for 48 hours or until reaching a stable weight. Record the oven-dried sub-sample weight of both grains and straw (g) immediately after taking out of the oven (do not let samples rehydrate!).

Note: Avoid over-packing samples in oven because good air circulation is needed for rapid and even drying.

Step 9: Grain and straw samples for quality analysis: take a 20–30 g sub-sample of oven-dried grain and place it in a ziplock bag, and take a 20–30 g sub-sample of oven-dried straw and place it in a paper bag. Both should be properly labelled. These samples can be used for further laboratory analysis.

2.3 Calculation

Step 1: Calculation of net harvest area in m^2

$$\text{Area (m}^2\text{)} = \text{Width (m)} \times \text{Length (m)} \qquad (4)$$

Step 2: Calculation of dry weight of grain

For small samples

$$\text{Dry weight of grain (kg/ha)} = \frac{\text{Dry weight of grains (g)}}{1000} \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (5)$$

For large samples

$$\text{Dry weight of grain (kg/ha)} = \left[\frac{\text{Total fresh grain weight (g)} \times \frac{\text{Dry weight of grain sub-sample (g)}}{\text{Fresh weight of grain sub-sample (g)}}}{1000} \right] \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (6)$$

Step 3: Calculation of dry weight of straw

$$\text{Dry weight of straw (kg/ha)} = \left[\frac{\text{Total fresh straw weight (g)} \times \frac{\text{Dry weight of straw sub-sample (g)}}{\text{Fresh weight of straw sub-sample (g)}}}{1000} \right] \times \frac{10{,}000}{\text{Net harvest area (m}^2\text{)}} \qquad (7)$$

Step 4: Calculation of total aboveground biomass (oven-dried weight) and harvest index

$$\text{Total aboveground biomass (kg/ha)} = \text{Dry weight of grain (kg/ha)} + \text{Dry weight of straw (kg/ha)} \qquad (8)$$

$$\text{Harvest index} = \frac{\text{Dry weight of grain (kg/ha)}}{\text{Total aboveground biomass (kg/ha)}} \qquad (9)$$

Note: If harvesting all biomass in the harvest area is not possible, there is an alternative method of sampling a representative number of stems (e.g. 50 stems) to determine harvest index and estimate biomass from grain yield and harvest index. For this method, please consult CIMMYT. 2013. *Yield and yield components: A practical guide for comparing crop management practices*. Maize and Wheat Improvement Center, Mexico. https://repository.cimmyt.org/xmlui/handle/10883/3387

Contributors

Mina Devkota (International Center for Agricultural Research in the Dry Areas [ICARDA]), Nele Verhulst (Maize and Wheat Improvement Center [CIMMYT])

Suggested citation: Devkota M and Verhulst N. 2022. Measurement of grain yield and aboveground biomass at maturity for crop cut at plot level, v1. Standard Operating Procedure 009. In: Saito K, Johnson J-M, Hauser S, Corbeels M, Devkota M and Casimero M. *Guideline for measuring agronomic gain key performance indicators in on-farm trials*. Africa Rice Center, Abidjan, Côte d'Ivoire.

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