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 standard operating procedure (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:

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

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.

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

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).

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

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).

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

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.

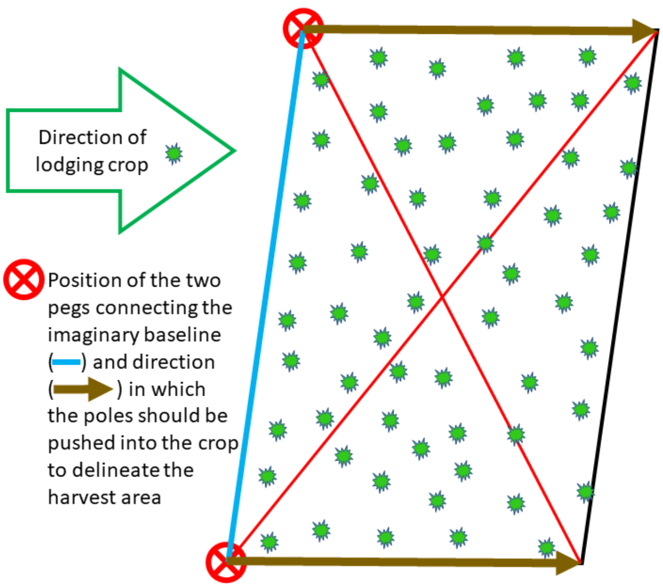


Figure 1. Examples of harvest areas with a deviation from right angles
As it is not possible to measure the actual angles in the field, the area can be calculated with the help of the diagonals and sectioning the harvest area into several triangles each with one right angle.

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.

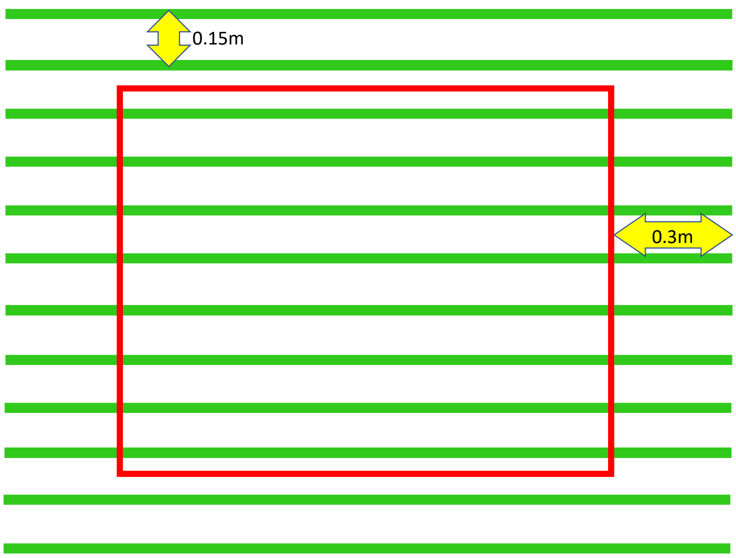


Figure 2. Example of a plot sown at 0.15 m row distance
Two rows on each side are borders and at least 0.3 m is allowed as a border at the start and end of the rows. The red rectangle delineates the maximum area of the plot that can be used to determine the yield.
Not to scale.

Medium-density crops in regular patterns

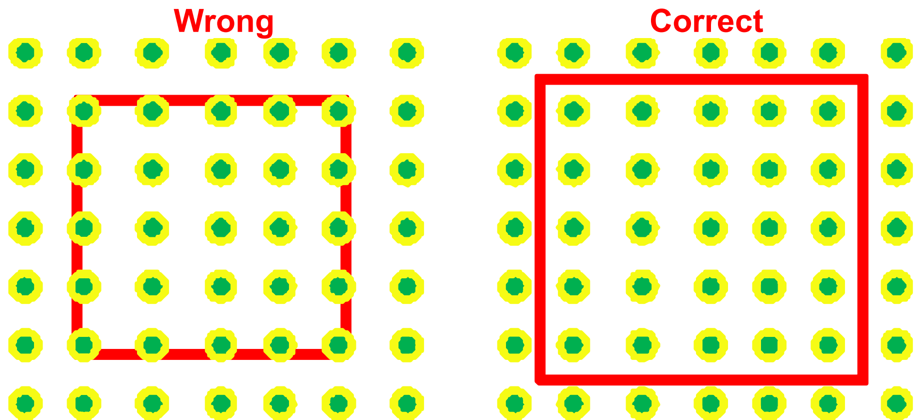
Similar to the situation in row-sown high-density crops, it is necessary to adjust the size and placement of the harvest area in medium-density crops to their planting patterns. However, there appears to be a misconception of where, within a plot, the boundaries between plants run. It can sometimes be 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, subplot 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 subplot 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).

$$A = 2 \times (a^2 \times 0.433) \qquad (5)$$

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

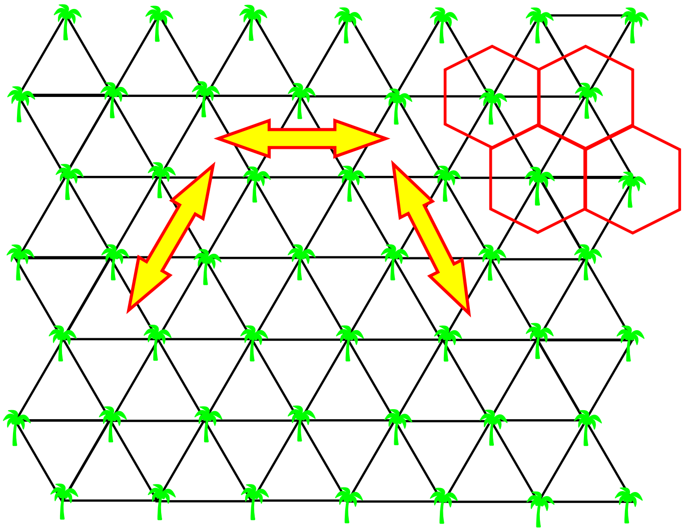


Figure 4. Example of the plant arrangement of a tree crop planted in a triangular pattern.
Plant rows are visible in three directions (yellow arrows). Each plant is allocated a hexagonal area (red lines).

Crops sown or planted in irregular patterns

Irrespective 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.

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

and

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

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 pulses 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.

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.

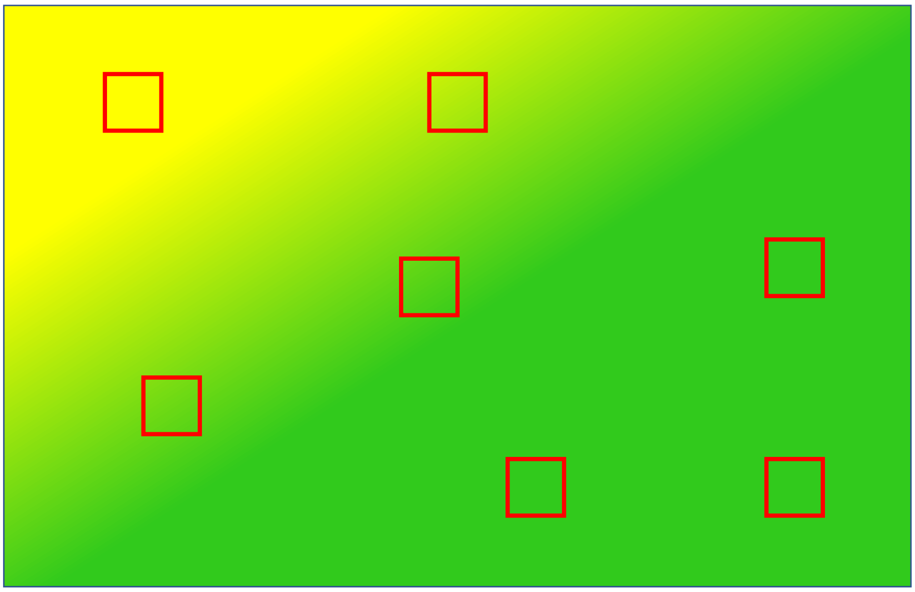


Figure 5. Example of a field with a gradient in crop performance from very good (green) transitioning into a poorer growth portion (yellow)

Red squares are sampling frames.

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 ‘subplots’, 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 subplot.

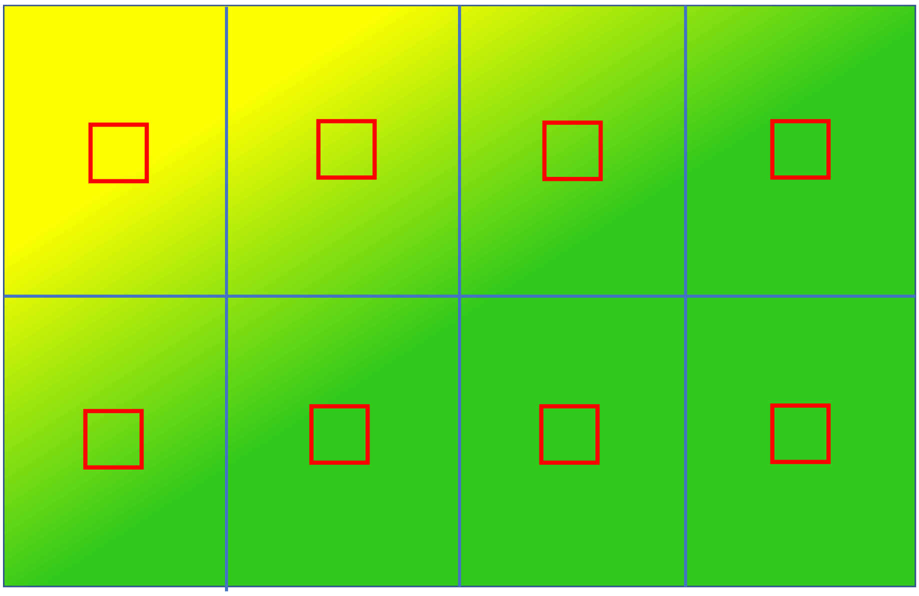


Figure 6. Example of a field with a gradient in crop performance sectioned into eight equal sized subplots and one sampling frame in each section

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.

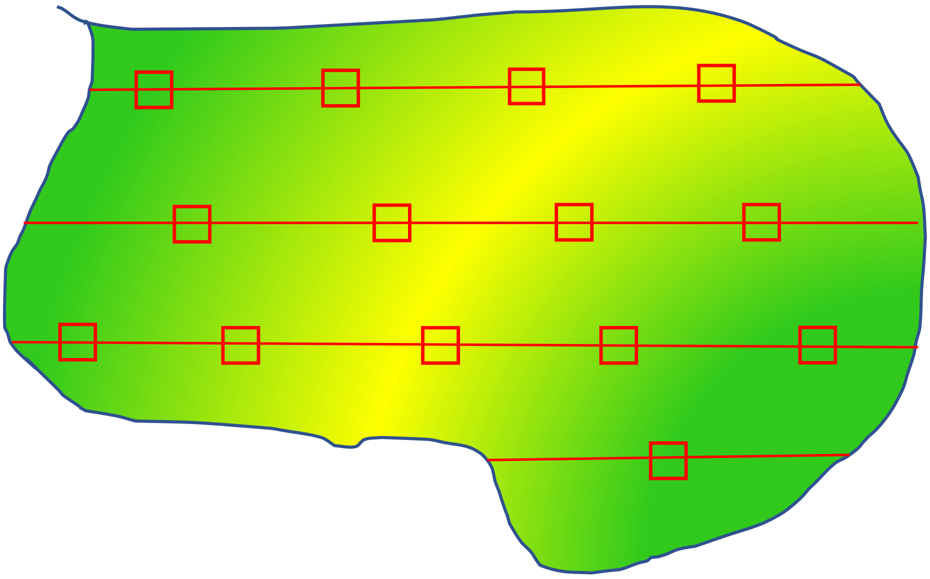


Figure 7. Example of an irregularly shaped field with a gradient of crop performance in two directions

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

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Suggested citation: Hauser S and Saito K. 2023. 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*, v. 1. Excellence in Agronomy for Sustainable Intensification and Climate Change Adaptation Initiative.

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