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The yield gap of major food crops in family agriculture in the tropics: Assessment and analysis through field surveys and modelling

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ABSTRACT

Yield gaps of major food crops are wide under rainfed family agriculture in the tropics. Their magnitude and causes vary substantially across agro-ecological, demographic and market situations. Methods to assess yield gaps should cope with spatio-temporal variability of bio-physical conditions, management practices, and data scarcity under smallholder conditions. Particularly challenging is to determine the most relevant methods for estimating potential (Y_p) and water-limited (Y_w) yields against which actual yields (Y_a) are compared. We assessed yield gaps of main staple rainfed crops across contrasting family farming systems in Senegal (millet, subsistence oriented systems), central Brazil (maize, market oriented systems) and Vietnam (maize, market oriented systems and upland rice, subsistence oriented systems). In each region, actual aboveground biomass, Y_a and yield components were measured over 2–3 agricultural seasons in a network of farmers' fields, covering the diversity of soils and farmers' management practices. Y_p and Y_w were calculated using a simple ad hoc crop simulation model (potential yield estimator, PYE) that was calibrated for each situation with observed and secondary data. Maize yields measured on farmers' fields were on average relatively high in market oriented systems, but extremely variable (4.14 ± 1.72 Mg ha^{-1}). In contrast yields of crops of subsistence oriented systems were very low (0.80 ± 0.54 Mg ha^{-1} and 0.80 ± 0.47 Mg ha^{-1} for millet and upland rice, respectively). $Y_a - Y_p$ was 0.15 for millet in Senegal, 0.33 for upland rice in Vietnam, 0.26 for maize in Vietnam, and 0.46 for maize in Brazil. In Vietnam, there was little difference between Y_w and Y_p suggesting a low incidence of water constraints. The gap between Y_a and Y_w was equal to (millet in Senegal) or twice (maize in Vietnam and Brazil) the difference between Y_w and Y_p, indicating that yield gaps depend strongly on factors other than global radiation, temperature, rainfall and soil water holding capacity. Previous studies in the case study areas showed that the main causes of yield gaps were poor soil fertility and weed infestation related to the inability of farmers to access chemical inputs. Simple methods to estimate Y_w and Y_p, such as the values at the 90th percentile of Y_a, or a bilinear boundary function fitted between seasonal rainfall and the best farmers' yield both led to strongly underestimated yield gaps. Y_w and Y_p estimated with a crop simulation model appeared to be more accurate, even in situations of relative scarcity of field data to calibrate cultivar-specific model parameters.

1. Introduction

Tropical agriculture faces particular challenges when it comes to achieving the potential yield of major food crops. Many tropical agro-ecosystems are characterised by strongly weathered, inherently poor Oxidic and Kaolinitic soils, acid and often also young soils formed on resistant minerals present in coarse textures (Sanchez, 1976). Rainfall patterns vary from those of dry and semi-arid areas with unreliable distributions, to those with excess rainfall interrupted only by a brief dry season. The latter, together with the absence of frost periods allows weeds, pests and diseases to complete their cycle many times during the year. Agricultural production in the tropics takes place to a large extent in resource-constrained family farming systems. The diversity of farms of this type is particularly high, even within relatively small regions, and this translates into highly diverse management strategies applied at field level. Farmers' priorities and objectives are not always to maximise crop yields but sometimes just to minimise production risks (Hardaker et al., 1997). Additionally a wide diversity of social traditions and local institutions govern the use of natural resources (Colding et al., 2003). As a result, the yields of major food crops are far below potential yields under rainfed family agriculture in the

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tropics. For example, Tittonell et al. (2008) reported average maize (*Zea mays* L.) yields in Kenya to be around 25% of the water-limited yield and Fermont et al. (2009) reported for cassava (*Manihot esculenta* Crantz) in Uganda and Kenya average yields of around 40% of the water-limited yield. Yield gap analyses are particularly challenging in tropical agriculture due to uncertainties in estimating the reference yield against which to compare actual yields, and the lack of experimental references. The magnitude and the causes behind them are expected to vary across regions differing in agro-ecological, demographic and market situations. The mere determination of average farmers' yields under smallholder conditions poses challenges due to the high spatial variability that exists across and within farms and the wide inter-annual rainfall variability, especially in savannah zones (e.g. Prudencio, 1993; Affholder, 1997; Sultan et al., 2005). Yield gap analyses are often done statistically, using multivariate methods, through remote sensing or using crop simulation modelling (see Dore et al., 1997, 2008; Lobell et al., 2009; Boling et al., 2010). The latter consist of the simulation of the water-limited yield of a crop for a certain climate and soil, to be used as reference yield to estimate the yield gap, and of the effect of management factors to explore possible yield gains (e.g. Affholder, 1995; Rockström and Falkenmark, 2000; Bhatia et al., 2008). An important challenge for such model-based studies is the need for quantitative information and data to parameterise and test the crop simulation models. While such information may be available from scattered experimental stations, most parameter values of current crop simulation models are rarely measured in developing countries of the tropics, particularly in Africa (Tittonell et al., 2010). Methods to assess yield gaps should cope with spatio-temporal variability and scarcity of crop yield data from family agriculture in these regions.

We present a comparative analysis of yield gaps across family farming systems that cover a wide diversity in terms of agro-ecological conditions and degrees of agricultural intensification in the tropics. To be able to compare yield gaps across regions, we propose to use a common and relatively simple methodology based on field surveying and crop simulation modelling. Our objective is to document and analyse the degree of yield variability under farmers' conditions and the pertinence of using crop simulation modelling to establish the reference potential yield, as compared to the other methods such as: (i) calculating the yield at the 90th percentile of farmers' yield distributions, and (ii) boundary function analysis based on the relationship between farmers' yields and water supply (Lobell et al., 2009; van Ittersum et al., 2013). We discuss the advantages and shortcomings of these methods, the causes behind yield gaps and the value of yield gap analysis as a concept to guide agricultural research in the tropics.

2. Methods

Actual aboveground biomass, grain yields (Y_a) and grain yield components were measured over two to three agricultural seasons in selected study areas in Brazil, Senegal and Vietnam. Yields were measured in a network of plots delineated within farmers' fields, covering the diversity of soils and management techniques. Potential (Y_p) and water-limited (Y_w) yields were calculated for each plot using a simple dynamic crop simulation model calibrated through an approach combining parameters retrieved from the literature and the use of observed data sets. This allowed us to calculate for each plot the absolute yield gap ($Y_w - Y_a$), the relative yield gap ($(Y_w - Y_a)/Y_w$) and the relative yield Y_a/Y_w, and to study their distribution within and across sites.

2.1. Case studies

We chose to compare four case studies with highly contrasting agro-ecological environments, farming systems and covering different cereal crops. The case studies were located in three regions: the centre-west region of Senegal (13°05′N–15°22′N, 14°12′W–16°46′W) with pearl millet (*Pennisetum glaucum* (L.) R. Br.) as the main crop, the district of Silvânia (16°46′S, 48°51′W), spread over 2000 km^2 in the savannah region of Central Brazil, with maize as the cornerstone of the farming systems, and the Cho Don and Van Chan districts in the mountainous area in the north of Vietnam (22°12′N, 105°34′E and 20°44′N, 100°30′E, respectively). In the latter region, two farming systems were analysed, one based on upland rice (*Oryza sativa* L.), and the other on maize. Our choice of the case studies allowed us to cross-analyse two levels of crop water constraints with two levels of market integration of the farming systems. Rainfall was expected to strongly limit crop growth in Senegal and to a lesser extent in Brazil, whereas under the humid and relatively cooler conditions of the mountainous region of Vietnam it was expected that water was not a limiting factor. In the case studies with maize, the farmers were linked to markets and the crop was grown as a cash crop, whereas in the two other case studies, millet and upland rice were primarily grown for subsistence food production. The four case studies are described in more detail below.

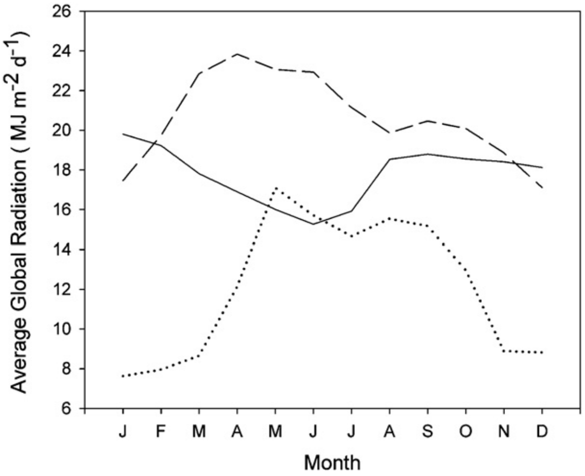

Fig. 1. Monthly global radiation of study regions in Senegal (dashed line), Brazil (solid line) and Vietnam (dotted line), respectively averaged over 1990–1991, 1994–1997 and 2004–2005 periods.

In the Senegalese case study pearl millet, groundnut (*Arachis hypogaea* L.) and niebe (*Vigna unguiculata* L.) are the main crops, grown by smallholder farmers on mostly sandy soils of low fertility. The heterogeneity of soils in the region resides mainly in the clay content and the resulting soil water storage capacity. The climate is semi-arid throughout the zone with a steep gradient of increasing annual rainfall from north (300 mm) to south (800 mm). Rainfall during the two years (1990–1991) of the field surveys were representative for the region (Table 1). The growing season extends from July to early October. Global radiation varies from 20 to 24 MJ m^{-2} d^{-1} during the growing season (Fig. 1). Crop management is done manually or using animal traction, without any use of mineral fertilizer, improved seeds, pesticide or other form of external inputs. The diversity in crop management relates mainly to the timing and effectiveness of farmers' interventions as determined by the amount of draught power and human labour force available, and by the amount of manure used. The latter depends on the size of the cattle herd owned, or on the arrangements established with neighbouring pastoral communities. Manure is commonly concentrated on "home fields" which constitute a circular area of more fertile soils around the villages. A second circular area of fields receives manure one out of two or three years, while more remote fields are seldom or never manured.

Table 1
Mean annual rainfall in each case study and annual rainfall amounts during the experimental periods (average values from the recordings with the rainfall gauges).

Case study	Mean annual rainfall (mm)	Number of rainfall gauges	Season	Annual rainfall during the experimental periods (mm)
Brazil-maize	1500	10	1994–1995	1226–1651
			1995–1996	819–1361
			1996–1997	1147–1732
Senegal-millet	300–800[a]	13	1990	203–481
			1991	197–621
Vietnam-maize	2200	3	2004	974–1316
			2005	2142–2354
Vietnam-upland rice	2200	3	2004	707–1420
			2005	1196–2278

[a] Corresponds to the fact that the study area covers a region with a strong rainfall gradient, in which exist several weather stations of the national meteorological service.

In the Brazilian case study the climate is classified as sub-humid with a total annual rainfall of about 1500 mm. The years (1994–1997) during which the field surveys were conducted were relatively dry, with annual rainfall amounts ranging between 38% and 73% of the average amounts (Table 1). Rain occurs during a single rainy season extending from October to April, but often with the occurrence of dry spells that are known to affect crop yields. Global radiation varies between 18 and 20 MJ m^{-2} d^{-1} during the growing season (Fig. 1). Ferralsols that are chemically poor but have good physical properties, prevail on the flat and smoothly undulating plateaus of Central Brazil, which favours the practice of large-scale, mechanised agriculture and irrigation. The case study area is, however, characterised by river valleys that occur in between the plateaus, with alluvial soils of good chemical and physical fertility in the valley bottoms, and with Cambisols of highly variable physical and chemical properties on the eroded slopes. Family farms are established in these valleys, growing maize as the main crop. During the time of data collection crop management was rapidly changing from manual and animal traction-based cropping with no use of external inputs to more intensive, mechanised systems with relatively high rates of chemical fertilizer applications (Affholder, 2001; Bainville et al., 2005).

In the two Vietnamese case studies, the climate is humid with an average total annual rainfall of 2200 mm. However, the two years (2004–2005) during which the field surveys took place, were relatively dry (Table 1). The growing season extends from March to December. Global radiation varies between 10 and 17 MJ m^{-2} d^{-1} during the growing season (Fig. 1). Soils are either fertile brown soils on limestone or poor Ferralsols on metamorphic rocks. Similar to the Brazilian case study, most of the farms were undergoing dramatic and rapid changes from subsistence towards market-oriented farming at the time of our data collection, resulting in cropping systems with varying levels of fertilizer use. Most farms have land both in the irrigated valley floors and on the mountainous slopes. They grow irrigated rice in the lowlands, with the double purpose of providing the food base for the family and generating a marketable surplus. Less than two decades ago, the slopes were mostly devoted to upland rice cultivation using slash and burn practices in order to complete the household's food needs not covered by the irrigated rice crop. However, the agricultural policy set by the government in the 90s led to significant intensification of the irrigated rice systems so that most farms no longer needed to grow upland rice. Instead, they increasingly grow maize, often in two consecutive cycles per season on the same piece of land, as feed for an income generating pig raising activity. Fertilisers and improved seeds are commonly used but crop cultivation operations remain exclusively manual, because the steep slopes prevent the use of animal or mechanical traction.

The second case study in Vietnam deals with the poorest farmers in the same region who have no or very small areas of irrigated land. These farmers were not able to benefit from the emerging market for maize and/or pigs and remained subsistence oriented. At the time of our study, they were still growing upland rice on sloping land to satisfy the household's needs, without any external input and using manual cultivation techniques.

2.2. Sampling of farms, fields and plots within fields

In each of the study regions, a farm/field survey was conducted to assess the local cropping conditions and crop growth performances. Farms were selected so as to cover (i) the local diversity in availability of production assets, land and labour, and (ii) the local diversity of soils. The selection was done on the basis of pre-existing farm typologies with the number of farms selected in each study region depending on the number of classes in the typologies. On average 6 farms were selected per farm type. On each farm, a number of fields (3 on average) were selected to cover the diversity of soil conditions on the farm (based on topography and local soil classifications). In each field, two to three rectangular plots of circa 25 m^2 (maize, millet) or 10 m^2 (rice) were delineated at the beginning of the cropping season so as to represent the apparent heterogeneity of soil conditions (field scale topography, variations in colour, crusting, stone or gravel content of the soil surface, residual biomass, all being visually evaluated) in the field. The size of the plots was a compromise between the objectives of maximising the precision of measurements on each plot (some of the measurements being destructive) and of minimising intra-plot heterogeneity.

The farm and field surveys were conducted during two (Vietnam and Senegal) or three (Brazil) agricultural seasons (i.e., the annual cycle of agricultural production that may start a given year and ends the next year in the southern hemisphere). We used different agricultural seasons at each site as a means to account for the diversity of the environmental conditions (other than those of the soil: i.e., climate, pests, etc). Consequently, the elementary unit of the analysis carried out in the present study is the small field plot of an agricultural season. A total of 790 of these elementary units resulted from the sampling procedure described above.

2.3. Measurements performed on the plots and indicators for occurrence of constraints

The observations and measurement on each field plot of the survey aimed at quantifying input parameters/variables to run the crop growth simulation model (see Section 2.4) and output variables for allowing comparisons between model simulations and field observations. In addition, technical crop management practices and the environmental characteristics possibly explaining yield gaps were recorded, using a diagnostic questionnaire with local key informants. In this way causes of local yield variations across fields and years were investigated. Soil samples were taken in each plot and basic physical and chemical characteristics were determined. At 10, 30, 60, 90, and 130 days after sowing, the three predominant weed species, weed infestation level, and disease/pest damage (using a five-level scale in both cases) were recorded for all plots. Dates and descriptions of all soil and crop management operations were also recorded, as well as the dates of the main crop phenological stages. Global radiation, temperature, wind velocity and air humidity were recorded at a central location in each study region using an automatic weather station. Precipitation was measured on a daily basis with gauges located at most one kilometre away from the field plots. At maturity, yield and the major yield components were measured. At each plot, the number of plants per unit area was counted and total aboveground biomass was measured by weighing the fresh weight of the total biomass and taking a subsample of 1 kg for moisture determination at the laboratory. All cobs (maize) or panicles (millet and rice) of the plots were taken away to the laboratory for threshing and determination of total grain yield at 13% moisture content (Y_a) and seed weight (W1S). The number of seeds per unit area was obtained as Y_a/W1S.

2.4. Model used

We opted for building an ad hoc crop growth model as recommended by Sinclair and Seligman (1996, 2000). Our aim hereby was to keep the model as simple as possible, not overloaded with unnecessary details, with minimum data requirements and with the re-use of existing model components, and to facilitate virtual experiments based on principles of interfacing between models and databases (Affholder et al., 2012). The model built, PYE (potential yield estimator, http://ur-sca.cirad.fr/produits-et-services), was written in VBasic under Microsoft Access. It simulates potential crop growth and yield as defined by van Ittersum and Rabbinge (1997) i.e., under idealised conditions where the crop is maintained free of any growth limitation other than temperature, solar radiation, and rainfall in case of rainfed crops, and considering a standard stand density. It was validated for rice and maize against observed data of crop phenology, leaf area index, aboveground biomass and grain yield in plots maintained, respectively, in potential growth conditions (Luu Ngoc Quyen et al., submitted for publication) and water-limited conditions (Luu Ngoc Quyen, 2012). PYE runs on a daily time step and takes its whole crop development and growth module from STICS (Brisson et al., 1998, 2003), which has been validated against experimental data of Y_p and Y_w for maize (Brisson et al., 2002) and pearl millet (Macena da Silva, 2004). PYE takes its whole water balance module from Sarra (Forest and Clopes, 1994; Affholder, 1997), also used in the more recent version of the model, Sarrah (Dingkuhn et al., 2003). The water balance module of Sarra is based on the classical 'tipping bucket' approach (van Keulen, 1975) and is very similar to the one used in STICS, hence the possibility to consistently couple the Sarra water balance module with the crop module of STICS while reusing many standard parameters of the latter. The water balance module of Sarra was preferred to that of STICS as the former proved to provide reliable estimates of available soil water in the root zone, the fraction of transpirable soil water (FTSW), soil evaporation, and transpiration under pearl millet in a semi-arid environment (Affholder, 1995, 1997) and under maize in a subhumid tropical environment (Affholder et al., 1997). Moreover, it accounts for the interaction between root growth and the seasonal descent of the wetting front of the soil, a feature that proved to significantly affect crop growth in tropical environments with a relatively long dry season and where the soil profiles are generally at or below wilting point at the onset of the cropping season (Affholder, 1995). Under potential growth conditions PYE calculates crop phenology and potential leaf area index as determined by thermal time. Potential growth rate (GR0) is obtained as a function of intercepted photosynthetically active radiation (RAINT), daily average air temperature and Ebmax, a maximal radiation conversion coefficient:

$$\mathrm{GR0} = (\mathrm{Ebmax} \times \mathrm{RAINT} - 0.0815 \times \mathrm{RAINT}^2) \times F(T),$$

where $F(T)$ is a parabolic function of temperature using the crop specific parameters TCmin, TCopt and TCmax, respectively the minimal, optimal and maximal temperature for radiation-to-dry matter conversion efficiency.

Under water-limited conditions potential daily increase in leaf area index and GR0 are both multiplied by a water stress coefficient which is a bilinear function of FTSW with a threshold value as in Allen et al. (1998).

Grain yield is calculated using a simple harvest index (HI) approach coupled with a sink limitation (Brisson et al., 1998). HI is first calculated as a function of the duration of the grain filling stage, using a crop specific daily rate of increase in HI, and a crop specific maximal HI (IRmax). Grain yield is then calculated as the minimal value between the one resulting from this HI approach and the product of a crop specific maximal weight of one seed (W1Smax) and the simulated value of the number of grains per unit area (Ngrain). The latter is calculated as a linear function of Vitmoy, the simulated growth rate averaged over the flowering stage:

$$\mathrm{Ngrain} = \mathrm{Cgrain} \times \mathrm{Vitmoy} + \mathrm{CgrainV0}$$

The two parameters (Cgrain and CgrainV0) of this linear function are cultivar dependent parameters.

2.5. Model calibration

Several crop growth models (e.g. DSSAT (Jones et al., 2003), APSIM (Keating et al., 2003), STICS (Brisson et al., 2003)) are based on the principle of a potential growth reduced by stress coefficients, and among them many are based on the same general principles as PYE regarding phenology, radiation interception, its conversion into biomass, partitioning to grains, and soil water dynamics. As a consequence, most of the model parameters used in PYE are analogous or identical to those used in these models. Additionally, the models based on the above principles have been proven to be valid over a wide range of environments and cultivars when evaluated against experimental data with growing conditions free from other limitations than radiation, temperature and rainfall. As a consequence, a broad experience exists on a number of non-cultivar-specific model parameters that are commonly used in these kinds of models, and for which consistent values are available in the literature. For parameters belonging to this category, we used values from published studies in which the experiments were explicitly designed to estimate these parameters (Table 2). Values for TCmin, TCmax, Ebmax, IRmax, W1Smax, the maximal leaf area index (LAImax), and the extinction coefficient of photosynthetically active radiation (Extin) were taken from studies where the crops had been maintained under potential growing conditions. Values for Kmax, the crop coefficient applied to the Penman–Monteith values of reference potential evapotranspiration to calculate potential crop evapotranspiration, were taken from the FAO guidebook on crop water requirements (Allen et al., 1998) following the 'single coefficient approach' with adjustments for air relative humidity, wind speed and crop height. However, a number of PYE parameters are cultivar-specific or particular to the model so that no reliable values could be found in the literature. The PYE model was calibrated for this second category of parameters using the data sets from the farmers' fields of our case studies. These parameters include thermal time constants that are related to the simulation of phenological development stages, which were calibrated for each cultivar by fitting simulated dates of the phenological stages to

Table 2
Literature-based values of the main parameters used in the YGE model. Figures between brackets indicate the bibliographic references.

Parameter	Description	Unit	Brazil	Senegal	Vietnam	
			Maize	Millet	Upland rice	Maize
TDmin	Minimal temperature for development	°C	6 (1)	11 (2,3)	9 (4)	6 (1)
TDmax	Maximal temperature for development	°C	28 (1)	47(2,3)	40 (4)	28 (1)
TCmin	Minimal temperature for radiation-to-dry matter conversion efficiency	°C	8 (1)	10(5)	10 (4)	8 (1)
TCmax	Maximal temperature for radiation-to-dry matter conversion efficiency	°C	42 (1)	47 (5)	42 (4)	42 (1)
TCopt	Optimal temperature for radiation-to-dry matter conversion efficiency	°C	25 (1)	33 (5)	29 (4)	25 (1)
Ebmax	Coefficient of maximal net radiation conversion		4 (6)	3.4 (7)	2.6 (8)	4 (6)
IRmax	Maximal harvest index		0.56 (9)	0.30 (10)	0.38 (11)	0.56 (9)
W1Smax	Maximal one-seed weight	g	0.342 (12)	0.010 (13)	0.034 (14)	0.342 (12)
Kmax	Maximal cultural coefficient		1.17 (15)	1.25 (15)	1.12 (15)	1.11 (15)
LAImax	Maximal leaf area index		6 (16)	6 (17)	5 (18)	6 (16)
Extin	Extinction coefficient		0.7 (16)	0.65 (19)	0.5 (20)	0.7 (16)
RZmax	Maximal root depth	cm	180	200	150	180

1: Affholder (2001); 2: Clerget et al. (2007); 3: Ong (1983); 4: Luu Ngoc Quyen et al. (submitted for publication); 5: van Oosterom et al. (2001) citing Garcia-Huidobro et al. (1982), Mohamed et al. (1988); 6: Brisson et al. (1998); 7: calibrated against simulations using Sarrah, Sultan et al. (2005); 8: Boonjung and Fukai (1996); 9: Hay and Gilbert (2001); 10: Bidinger et al. (1994); 11: Saito et al. (2007); 12: Golam et al. (2011); 13: Diouf (1990); 14: Asai et al. (2009); 15: Allen et al. (1998); 16: Lindquist et al. (2005); 17: Ong and Monteith (1985); 18: Bouman et al. (2005); 19: van Oosterom et al. (2002); 20: Dingkuhn et al. (1999).

observed ones. Other cultivar-specific parameters are Cgrain and CgrainV0 that determine the value of Ngrain as a function of Vitmoy (see Section 2.4). Cgrain and CgrainV0 were estimated for each cultivar by fitting the simulated number of grains to the boundary line of observed Ngrain plotted against simulated Vitmoy (e.g. Fig. 2). By applying this procedure, we assumed that, in the plots defining the boundary line, Ngrain was determined by temperature, radiation, water stress and cultivar characteristics only. The consequences of this assumption on the reliability of our Y_p and Y_w estimates are discussed in Section 4.1.

Boundary line models were fitted to the maximum possible value of the dependent variable (e.g. grain yield) at each level of the independent variable (e.g. rainfall) following the method of Shatar and McBratney (2004).

2.6. Model runs and additional calculation

For each of the 790 elementary units from the four case studies we used the PYE model to calculate (1) the potential yields Y_p, i.e. simulated aboveground biomass and grain yield as determined by radiation and temperature for the cultivar and sowing date observed in the plot, and (2) the water-limited crop yields Y_w, i.e. simulated aboveground biomass and grain yield as in the preceding but taking additionally into account rainfall and soil water balance limitations under no water run-off conditions; the soil water holding capacity being parameterised on the basis of field plot measurements. For each site and crop, plant density was parameterised using the plant density recommended by local services of agricultural extension.

In the Vietnamese case studies where plots were located at different altitudes, daily average temperature recorded at the central weather station was corrected for altitude using the formula: $T_{plot} = T_{ws} + 0.6(A_{ws} - A_{plot})/100$, where T_{plot} is the daily average temperature estimated for the plot at a given altitude, A_{plot}, T_{ws} the daily average temperature recorded at the weather station, and A_{ws} the altitude of the location of the weather station (Baker, 1944).

In the Vietnamese case study, we, respectively, summed up the observed and simulated yields of maize grown in two consecutive cycles on the same field during one agricultural season, as this was frequently the case.

3. Results

3.1. Yield variability in farmers' fields

Average grain yields in farmers' fields and their variability distribution differed widely between sites and crops (Fig. 3). Maize grown as a commercial crop in the Brazilian and Vietnamese case studies showed yields following an approximately normal

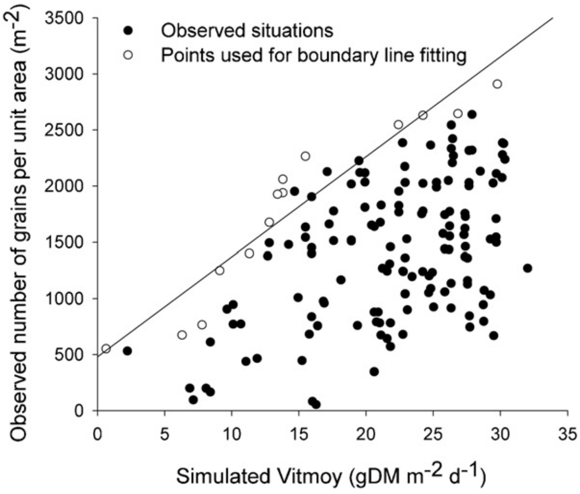

Fig. 2. Determination of Cgrain and CgrainV0 values by plotting the observed number of grains per unit area against the simulated mean growth rate during flowering. Cgrain is the slope and CgrainV0 the intercept of the boundary line of the data cloud.

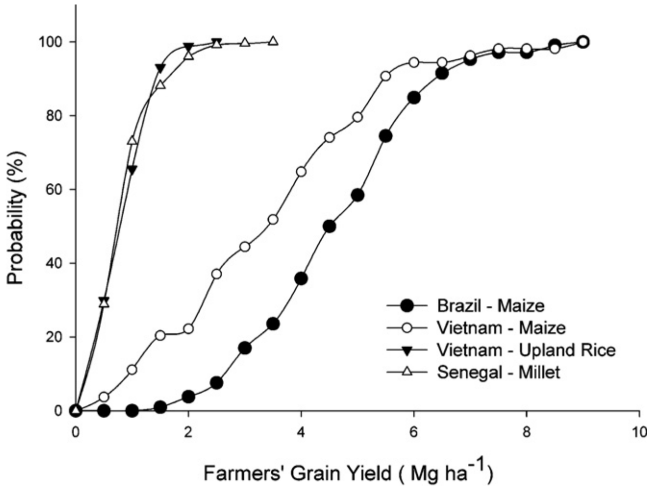

Fig. 3. Cumulative probability distribution of farmers' grain yield according to country and crop.

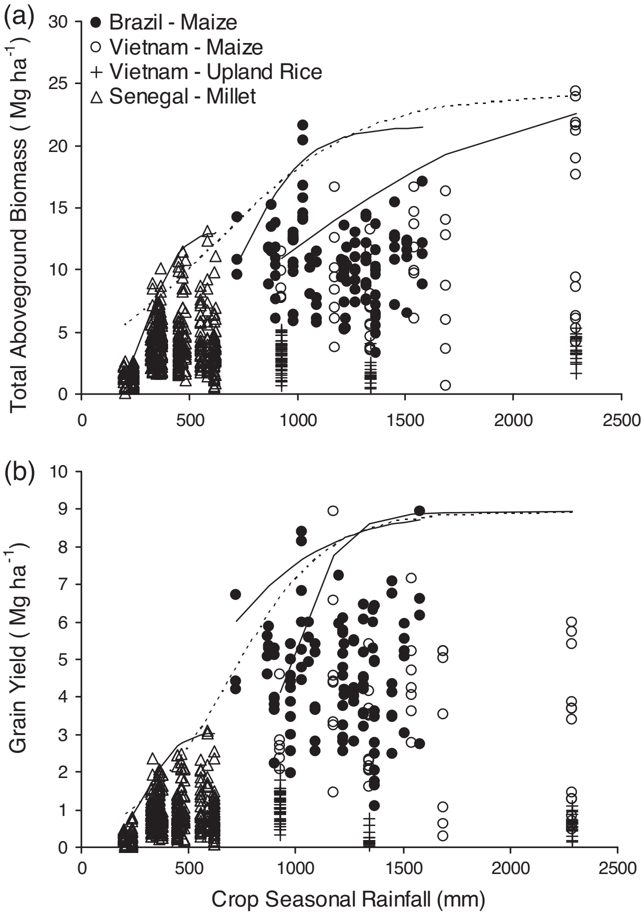

Fig. 4. Farmers' total aboveground biomass (a) and grain yield (b) plotted against seasonal rainfall. The three solid lines are the envelop curves of the different crop/country combinations (except upland rice/Vietnam). The dashed line is the envelop curve of the entire data set.

distribution, with higher median (4.50 vs. 3.41 Mg ha^{-1}) and average (4.57 ± 1.49 vs. 3.32 ± 1.85 Mg ha^{-1}) values at the former site. Grain yields of upland rice in Vietnam (median 729 kg ha^{-1}; average 801 ± 474 kg ha^{-1}) and pearl millet in Senegal (median 682 kg ha^{-1}; average 805 ± 539 kg ha^{-1}), both food-consumption oriented crops, exhibited remarkably similar, asymmetrical distributions with higher frequencies of observations in the lower percentiles. At both sites, about 70% of the farmers' fields yielded less than 1 Mg grain ha^{-1}, and in the case of pearl millet in Senegal yields were smaller than 2 Mg grain ha^{-1} in more than 95% of the fields surveyed.

Part of the yield variation across sites can be explained by their agro-ecological potential, notably rainfall and radiation (see Table 1 and Fig. 1). This is reflected by the maximum levels of crop productivity at each site, estimated through the upper boundary model fitted to the distribution of total aboveground biomass as a function of seasonal rainfall (Fig. 4a).

Maximum aboveground biomass values observed on farmers' fields were 23 Mg ha^{-1} for maize, 13 Mg ha^{-1} for pearl millet, and 6 Mg ha^{-1} for upland rice. The maximum grain yield values (Fig. 4b), which can be seen as first approximations to the potential yield levels of these crops in these locations and farming system contexts, were respectively 9 and 7 Mg ha^{-1} for maize in Brazil and Vietnam, 3 Mg ha^{-1} for pearl millet in Senegal and 2 Mg ha^{-1} for upland rice.

The maximum maize grain yields were achieved with threshold seasonal rainfalls of around 1500–1600 mm both in Brazil and Vietnam while maximum grain yields of pearl millet were obtained with around 600 mm in Senegal. Biomass and grain yields of upland rice in Vietnam were less sensitive to seasonal rainfall, presumably due to strong yield limitations by other factors, such as nutrients or biotic constraints. The dashed line in Fig. 4a and b was fitted to the entire dataset, all crops and locations confounded, and provides a good estimation of the water-limited yield that may be attained across these tropical environments with current technology and resources. In particular, the difference in maize productivity between Brazil (one cropping cycle per agricultural season) and Vietnam (two cropping cycles per agricultural season) may be to a large extent attributable to the effects of agronomic practices, genetic material and inputs. Moreover, while maize in Brazil is often allocated the best soils of a farm on relatively flat areas, maize in Vietnam is grown on slopes surrounding the fertile valleys that are preferentially cropped with irrigated rice. Substantial water-runoff and erosion are expected on such slopes that also contribute to the lower yields.

3.2. *Assessment of reference yields*

Four reference yields were calculated with the simulation model YPE to estimate yield gaps (Fig. 5) for each plot of the field surveys in the three case studies: (a) potential aboveground biomass yield, (b) potential grain yield, Y_p, (c) water-limited aboveground biomass yield, and (d) water-limited grain yield, Y_w. Simulated potential aboveground biomass of upland rice in Vietnam was lower than that of millet in Senegal and maize in Brazil, consistently with the lower radiation in the study area of Vietnam (Fig. 1) and the lower conversion and interception coefficients of upland rice compared to other cereals (Mitchell and Sheehy, 2000). The highest values were obtained for maize in Vietnam, despite the relatively lower solar radiation during the cropping season, as a result of the two crops per year on the same field. The difference between upland rice and the other crops was greater for simulated grain yield, both potential and water-limited. This difference came not only from the low biomass accumulation mentioned above, but also from the low values of the parameters Cgrain and CgrainV0 determining the number of grains per unit biomass accumulated. The resulting, remarkably low values of simulated HI and grain yield of upland rice in Vietnam are consistent with data reported from experiments with cultivars traditionally used in other mountainous regions of South East Asia receiving high amounts of fertilizers and under full weed control. For example, Saito et al. (2007) reported yields ranging from 2.2 to 2.8 Mg ha^{-1} and total aboveground biomass from 7.1 to 8.5 Mg ha^{-1} for different cultivars grown in near-optimal condition in the mountains of northern Laos. Other authors have underlined the low radiation use efficiency and low sink size of these traditional cultivars (Roder et al., 1998; Asai et al., 2009).

An advantage of using the simulated water-limited yield as reference is the fact that in the yield gap analysis it allows taking into account the variability in rainfall and soil water holding capacity. Such variability is reflected in the range of values on the *x*-axes of Fig. 5c and d. The simulated potential yield based solely on radiation and temperature as driving variables often predicts a narrow range of yields, as clearly seen in the case of pearl millet when comparing Fig. 5a with Fig. 5b and Fig. 5c with Fig. 5d. The two 'clouds' of simulated potential yields of maize in Vietnam correspond to the yield of one or the sum of two crop cycles. The range of values of potential yield and biomass (*x*-axes in Fig. 5a and b) is also larger in Vietnam than in the other cases, even when considering each of the two 'clouds' of Vietnam separately. This is due to the higher variations in temperature and radiation across fields in the mountainous area of Vietnam, as a result of the variations in elevation and sowing date. However, the range of simulated water-limited grain yields (from ca. 1 to 17 Mg ha^{-1}) was virtually twice as wide as that of the observed yields (from ca. 0 to 9 Mg ha^{-1}). Both for

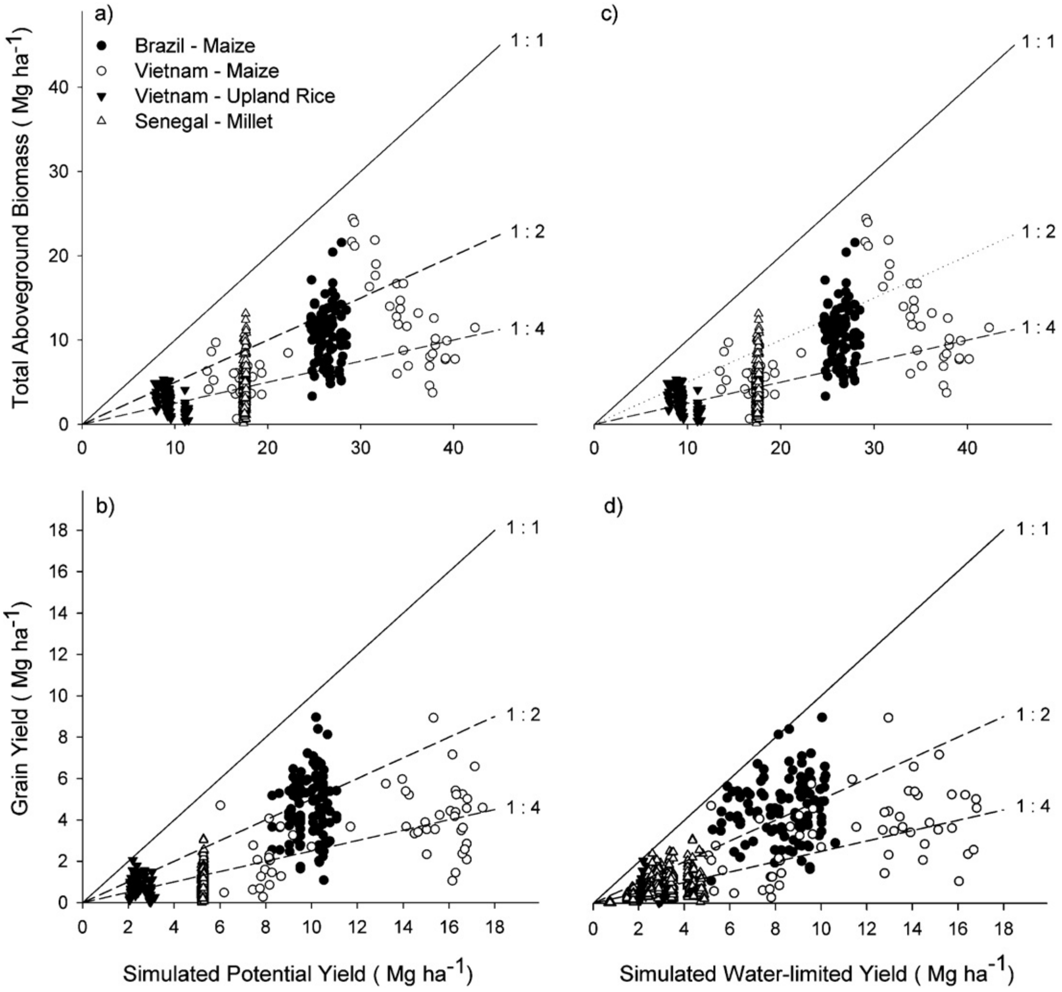

Fig. 5. Measured aboveground biomass (a and c) and grain yield (b and d) against corresponding simulated potential (a and b) and water-limited values (c and d).

aboveground biomass and grain yields, the gap between observed and simulated potential or water limited yields was in general wider at higher yield levels.

3.3. The magnitude of yield gaps across sites

Simulated potential yields were always considerably higher than maximum observed yields, particularly for the total aboveground biomass. Most observed biomass and grain yields fluctuated between 25% and 50% of the simulated potential, with the highest average value for maize grain yield in Brazil, which was on average 46% of the simulated potential. The average yield gap in absolute terms with respect to the water-limited grain yield potential ($Y_W - Y_a$) was 3.7 Mg ha^{-1} for maize in Brazil, 7.8 Mg ha^{-1} for maize in Vietnam, 2.2 Mg ha^{-1} for pearl millet in Senegal and 1.7 Mg ha^{-1} for upland rice in Vietnam (Fig. 6). Variability in observed grain yields was comparable to the variability in simulated water-limited grain yields of maize in Brazil and of upland rice in Vietnam, as can be seen by the width of their interquartile ranges in Fig. 6c. Variability in simulated water-limited yields was greater than in observed yields for maize in Vietnam and millet in Senegal. Fig. 6b and d shows the relative aboveground biomass and grain yields calculated with respect to potential and water-limited yields. Average relative yield (Y_a/Y_W) was 0.56, 0.30, 0.27 and 0.33, respectively for maize in Brazil, maize in Vietnam, millet in Senegal, and upland rice in Vietnam. The interquartile variability of relative biomass yields was comparable across crops, locations and methods of calculation, fluctuating around ±10%. Variability in relative grain yields depended on crop type, location and method of calculation, being generally wider when the relative yield was calculated with respect to the water-limited yield.

An alternative to using simulated potential or water-limited yields as reference to calculate yield gaps is the use of best yields on farmers' fields such as the value at the 90th percentile. When considering total aboveground biomass as well as grain yield, these values at the 90th percentile were always well below the corresponding simulated water-limited values (Fig. 7). The ratio of best farmers' aboveground biomass over water-limited aboveground biomass was 0.63, 0.76, 0.52 and 0.63 for maize in Brazil, maize in Vietnam, upland rice in Vietnam and millet in Senegal, respectively. The ratio of best farmers' grain yield over Y_W was 0.77, 0.48, 0.6 and 0.52 for maize in Brazil, maize in Vietnam, upland rice in Vietnam and millet in Senegal, respectively.

The two case studies with maize-based market oriented farming systems are remarkably contrasting with the two subsistence oriented cases with upland rice and millet. Water-limited biomass yields in the two former case studies (22.6 and 24.8 Mg ha^{-1} for maize in Brazil and Vietnam, respectively) were about twice as high as those in the latter case studies (8.9 and 10.1 Mg ha^{-1} for upland rice in Vietnam and millet in Senegal). Farmers' best and average biomass yields were both up to three times higher in the two market oriented case studies with maize than in the case studies with pearl millet and rice for food consumption. The contrast is even greater when grain yield is considered. Water-limited grain yield

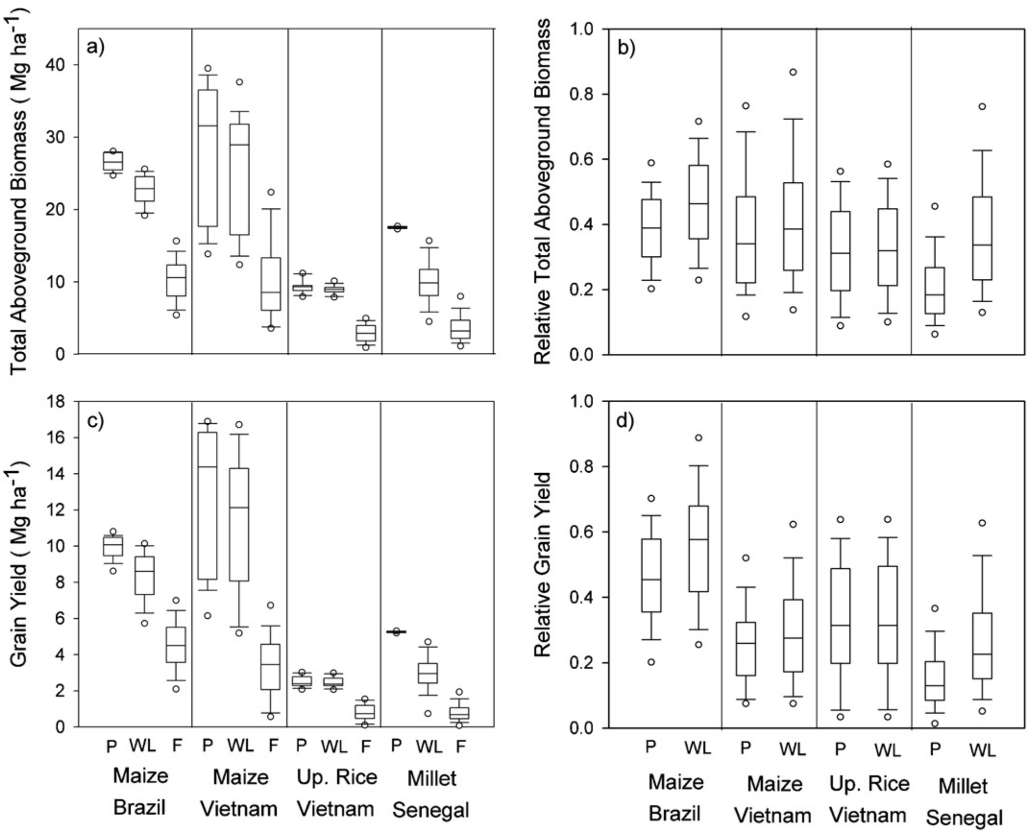

Fig. 6. Potential (P), water-limited (WL) and farmers' (F) total aboveground biomass (a) and grain yield (c) and their relative values with respect to simulated potential and water-limited aboveground biomass (b) and yield (d). Horizontal lines within the boxes: median; lower and upper boundary of the boxes: 25th and 75th percentiles; lower and upper error bars: 10th and 90th percentiles; points: 5th and 95th percentiles. Up. Rice: upland rice.

was three times higher in the two case studies with maize than in the case studies with millet and rice, the multiplicative factor rising up to around four when farmers' best and average grain yields are considered. The difference between average and best farmers' grain yields was around 2 Mg ha^{-1} for maize in Brazil and Vietnam, but best farmers' yields were much closer to the potential yields in Brazil (Fig. 7b). Best pearl millet grain yields obtained by farmers in Senegal were relatively close to simulated water-limited yields but relatively far from the simulated potential yields (Fig. 7b). The gap between simulated potential and water-limited yields provides an estimation of the strength of the water stress on crop production in this environment. The relatively important gap between average and best farmers' yields is attributable to nutrient and agronomic management and indicates that yields could be more than doubled with a more efficient use of available technologies.

4. Discussion

4.1. Measures of yield potential

Plotting observed aboveground biomass and grain yields against seasonal rainfall for the entire data set (dashed line in Fig. 4) suggests that a simple bilinear boundary function could serve as a first approximate of the water-limited yields of aboveground biomass and grain production for rainfed cereals. Such bilinear function (an approximate of the boundary curve) has a threshold of around 1000 mm above which yield potential (24.4 Mg ha^{-1} and 8.9 Mg ha^{-1} for aboveground biomass and grain, respectively) no longer increases. Below this threshold, the slope of the line is approximately 24 kg ha^{-1} mm^{-1} and 8.9 kg ha^{-1} mm^{-1} for aboveground biomass and grain, respectively. The latter figure is far below the slope of 22 kg ha^{-1} mm^{-1} presented by van Ittersum et al. (2013) using data from intensive cropping systems in the USA and Australia with irrigated maize and rainfed wheat, respectively. On the other hand, these authors also show data for rainfed maize in Kenya that fall below the boundary line of our study. It is, however, doubtful whether our bilinear boundary function of seasonal rainfall would apply to environments with radiation and temperature patterns that differ considerably from those of our case studies. Moreover, the boundary curve approach is likely to overestimate the water-limited yield potential for a given region, since it does not inform about possible soil physical constraints that affect water-limited yield potentials such as shallow soil depth or low soil water holding capacity, and which are difficult to overcome through improved farmers' management.

The best farmers' yields of a given region may give a better idea of what actually can be achieved under the normal edaphic conditions of that region (Lobell et al., 2009). Yet, the case may arise where high yields are obtained on some localised soils with the most favourable water retention characteristics, while a majority of farmers in the region deal with more adverse soils, with little chance to reach similarly high yields. It is also likely that the use of maximum farmers' yields as a proxy for potential yield is most appropriate in intensively managed cropping systems, with high levels of fertilizers and pesticide, where yield limiting factors such as nutrient deficiencies, insect attacks, diseases and competition with weeds are virtually eliminated. However, even then it is still improbable that a farmer reaches the water-limited yield potential, since optimal nutrient and pest management is quite impossible to achieve and in many cases economically not beneficial (e.g. Laborte et al., 2012). Moreover, under the conditions of family farms in the tropics farmers often cannot afford the best available technologies

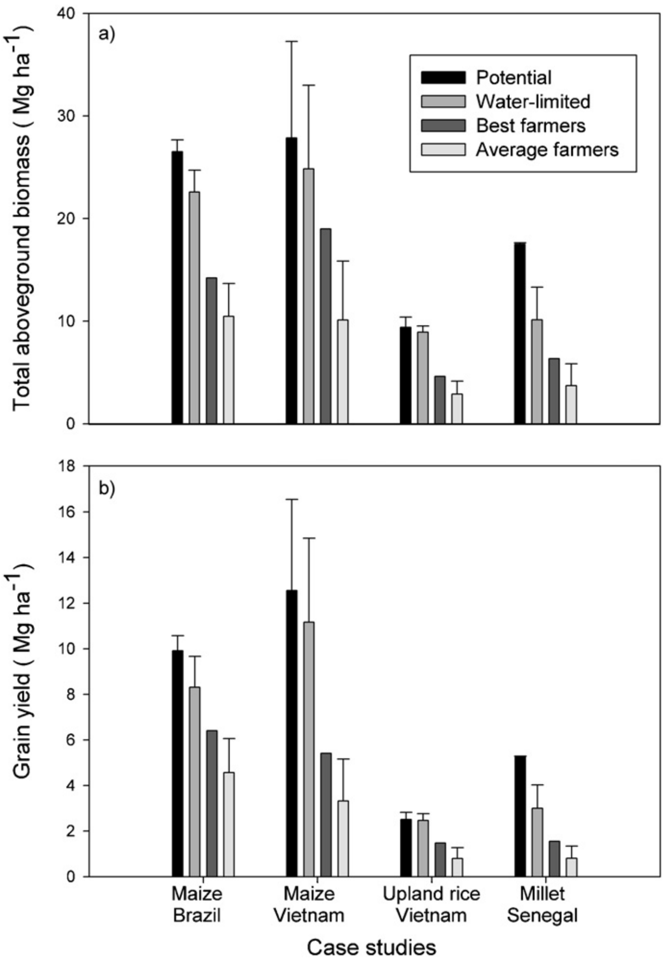

Fig. 7. Average potential, water-limited, best farmers' and farmers' yields in (a) total aboveground biomass and (b) grain, for each crop–case study combination. Best farmers' yield is the value at the 90th percentile of yield observed in farmers' fields. Error bars are standard deviation (not applicable to the 90th percentile value).

that would allow them to reach the yield potential. Our results (Fig. 7) show that farmers' best yields are considerably lower than the water-limited potential. In general, yield potentials obtained from best farmers' fields are related to best available and affordable technologies to the farmers and as such they also do not account for future innovative, more sophisticated crop and soil management practices.

The PYE model, which simulates crop growth and yield as determined by radiation and temperature for a given cultivar and sowing date, gives us the most reliable estimates of aboveground biomass yield potentials, since the simulated output mostly relies on a few crop parameters for which robust estimates are available in the literature, and on cultivar-specific thermal time constants that can be calibrated using observed crop phenological stages that are not expected to depend on management factors. It is evident that the quality of these aboveground biomass yield potential estimates is directly determined by the accuracy of the temperature and solar radiation records. In our case studies, weather recordings were done with accurate and well-located automated weather stations. However, in many tropical regions reliable meteorological data are missing because the geographic coverage of weather stations is incomplete or sometimes even non-existent. Assembled global meteorological databases using satellite imagery such as the database developed by NASA-Power (http://power.larc.nasa.gov/index.php) are a promising alternative source of continuous daily weather data, provided that they are properly evaluated for the region where yield potentials are to be estimated (White et al., 2008). Due to the lack of validation of our ad hoc PYE model against experimental Y_p and Y_w data, and more particularly, because of the assumptions we made with the calibration of the function that determines the number of grains per unit area, Ngrain, we acknowledge that our model estimates of Y_p and Y_w are subject to relatively high parameter uncertainties. It was assumed that for each cultivar in our data set there was at least a couple of plots for which the growth of above ground biomass during flowering stage was not affected by any factor other than temperature, radiation, and water stress which are simulated by the PYE model. Since this applies to a relatively short period of the crop cycle, this assumption is more likely to be valid than the assumption – on which the use of best farmers' yields is based – that the crop was not affected by any limitation other than temperature, radiation, and water stress throughout its entire cycle. Thus our assumption with the calibration of Ngrain may underestimate Y_p and Y_w, and hence the yield gap. Nevertheless, the values obtained with our ad hoc simulations are highly plausible with respect to the highest observed yields in our data set (see Fig. 5) and the highest yields recorded in field studies with comparable cultivars under similar environments (e.g. maize in Brazil (Scopel et al., 2004; Baldé et al., 2011) millet in west Africa (van Oosterom et al., 2002; Sultan et al., 2005), upland rice in South East Asia (Saito et al., 2007)).

Whatever the modelling approach retained for simulating the allocation of produced biomass to grains, it will involve crop-specific or cultivar-specific parameters that are currently not established as 'easy to calibrate parameters' against a set of field observed data on grain yield or yield components. It would certainly be worth comparing the main approaches for modelling biomass allocation to grains to identify which is the most reliable and robust under a range of climate and soil conditions. It is likely that without specific calibration experiments for grain allocation, in which farmers' cultivars are grown without any nutrient and pest limitations during at least the flowering to grain filling stages of crop development, the parameter error of grain allocation modules in crop models will remain relatively high.

For simulating the water-limited yield potential, the water balance component of PYE uses the tipping bucket approach which is known to be particularly robust, provided that no water runoff has to be considered and that reasonably good estimates of the soil water holding capacity and daily rainfall are available (van Keulen, 1975). We assumed zero runoff in our estimates of water-limited aboveground biomass and grain yield, thus considering runoff among the factors that are manageable by farmers. This is only partially true, since in some cases the investment necessary to fully control runoff may be economically unjustifiable. On the other hand, defining a representative level of runoff for a given region seems difficult and would be somehow arbitrary. Soil water holding capacity is far less subject to modifications by management practices, but is highly variable across landscapes. Therefore its spatial distribution is key information required when assessing yield potentials under rainfed conditions in a given region. However, few databases, especially for the tropics, incorporate this soil property.

The high variability of water-limited yields of maize in Brazil and Vietnam and of millet in Senegal (Fig. 6a) indicates that bio-physical constraints associated with rainfall and soil physical properties are important determinants of crop yields in these case studies. These factors, which for a large part are out of farmers' control, have to be taken into account when assessing the scope for yield improvement. We believe that this is true for many parts of the tropics: our case studies cover a wide part of the spectrum of tropical environments.

4.2. Magnitude of yield gaps

The limited number of agricultural seasons covered in our case studies prevented us from assessing the role of inter-annual variability of weather on actual yields. However, the seasons studied were not atypical (Table 1) and across our case studies yield gaps appeared much more determined by differences in farming systems than by differences in climate, as suggested by the remarkable similarity of yields distributions of upland rice in Vietnam under rainfall from 1000 to 2300 mm, and of millet in Senegal under 200–600 mm of rainfall. The case studies in Brazil and Senegal were carried out one and two decades ago respectively, but recent farm surveys in the same regions reported comparable cropping systems, including the cultivars, with stable or even lower yields (Balde, 2010; Mertz et al., 2011). The average relative grain yield (Y_a/Y_w) reported in the present study varied between 0.27 (millet in Senegal) and 0.56 (maize in Brazil) with a wide intra-site variation (Fig. 6). Overall, these values are considerably lower than the ones reported for intensive cropping systems, e.g. maize in the US (Grassini et al., 2011) or rice in China (Defeng, 2000) for which values of about 0.8 are reported. Lobell et al. (2009) suggested that yields of 80% of its potential are an approximate of the economic optimum level. The global literature survey done by these latter authors revealed a wide range of estimated relative yields (0.2–0.8) for maize, rice and wheat, with the highest relative yields in several wheat and rice regions where land is relatively scarce and population density high. It is known that this favours the use of land-saving technologies and intensification of the cropping systems, which generally leads to higher yields thus closing the yield gap (Cassman, 1999). It may also be expected that the closer the integration between production and input/output markets, the narrower the gap between best farmers' and potential yields as in the case of maize in Brazil and Vietnam in our study.

The fact that observed yields on farmers' fields were far below water-limited potential yields in all case studies indicates a great scope for intensification of cereal systems in the tropics. At the same time it raises the question why this yield gap is still so significant. In the two case studies with market oriented farming systems, the cultivars used by farmers were cultivars with relatively high harvest index and suited to high stand densities, with the sole purpose of grain production. In such context, relatively small yield improvement may be expected from changes in the cultivars used, as compared to expected impacts of improved soil management. In contrast, in the two other case studies, local cultivars of millet and upland rice are typically grown with relatively low harvest indices, suited to the double purpose of producing grain and straw for fodder, fuel and construction material. Under a future scenario of linking these farms to markets, it is likely that farmers will choose for cultivars with higher harvest indices, or simply for other crops, resulting in higher grain yields. This is what is observed, for example, in many areas of West Africa where maize is progressively replacing the traditional millet and sorghum crops (Kouressy et al., 2003). It is also what has happened in the mountains of Vietnam where the fields currently cropped with maize were less than a decade ago cropped with upland rice (Erout and Castella, 2004). In our study with upland rice in Vietnam, Y_w increases from 2.5 Mg ha^{-1} to 11.2 Mg ha^{-1} per year when replacing upland rice by maize often grown twice a year on the same field (Fig. 7b). Similarly, water-limited total above ground biomass increases from 8.9 Mg ha^{-1} to 24.8 Mg ha^{-1} (Fig. 7a). Thus in the case where crops are primarily grown for subsistence food production, a significant part of yield improvement may be expected from a change in cultivars, crops or cropping systems, which is not accounted for when using Y_w or water limited total above ground biomass of the currently grown cultivars as the ceiling yield. As a consequence, unless defining a theoretical crop to be used as a single reference throughout the world for yield gap estimates, it is likely that the room for yield improvement will be strongly underestimated when using the yield gap approach in regions where subsistence oriented farming systems with local cultivars predominate.

4.3. Causes of yield gaps

In the case study in Senegal, the causes of the yield gaps at field scale were identified using a basic cross-correlation analysis of yield gaps against indicators of biotic and soil constraints and crop management (Affholder, 1994). In fields with a low water-limited yield potential, poor soil fertility was the main factor explaining the yield gaps, while in fields with a relatively high water-limited yield potential, low soil fertility and weed infestation were the explanatory factors. Both low soil fertility and weed infestation are likely to be directly related to the low purchasing power of farmers and the resulting limited access to fertilisers and herbicides, and to the limited availability of labour on their farms (Ramaswamy and Sanders, 1992). Studies from other authors (Perez et al., 1998) in the same region also mentioned water runoff as a key factor explaining observed yield gaps. Even with improved access to fertilisers and other external inputs, closing the yield gap in this region will require that farmers combine improved soil fertility and weed management with water saving techniques at field (Sawadogo, 2011) and landscape level (Zougmoré et al., 2010) in order to reduce production risks induced by rainfall variability, which are expected to increase with crop intensification (Affholder, 1997; Rouw, 2004).

In the case study in Vietnam, Husson et al. (2004) used a similar approach as the one used in the Senegalese case study to identify the main causes of variability of upland rice yields between fields. Also here, the major explanatory factors for yield differences were weed infestation and soil fertility. Weed infestation was shown to increase with decreasing duration of the fallow period preceding rice cultivation and with increasing number of growing seasons with continuous cropping since the last fallow period. Soil fertility constraints were mainly low organic nitrogen content, soil compaction favouring runoff, and high rate of exchangeable aluminium limiting root growth. Bal et al. (1997) suggested that soil compaction in the region was related to overgrazing by buffaloes during the dry season, and that low soil organic nitrogen was due to the shorter fallow periods coupled with the absence of any fertilisation and the removal or burning of crop residues in the upland rice fields. To date, the causes of the maize yield gaps in the Vietnamese case study were not analysed.

In the case study in central Brazil, a detailed analysis of yield variations was carried out (Affholder et al., 2003). First, the model STICS (Brisson et al., 1998) was used to simulate water- and nitrogen-limited yield for each field. A cross-correlation analysis was performed to identify the main factors explaining the gap between observed yields and simulated water- and nitrogen-limited yields. These were aluminium toxicity in soils, weeds and soil waterlogging. Second, the model STICS was modified to account for the effects of these factors on maize growth. The resulting model was calibrated and tested against observed data on the field plots. A third step of the analysis consisted in a virtual experiment in which the effect of crop stand density, water and nitrogen limitations, and limitations due to weeds on simulated yield were evaluated separately (Fig. 8a). Additionally to these single effects, the interactions between the constraints were assessed using the same modelling approach (Fig. 8b). This showed, for instance, that weeds had a greater simulated negative effect on yield on fields with low maize stand density, where they could benefit from relatively higher global radiation at their early stage of growth, which placed them in a more favourable position in the competition with maize for light, water and nitrogen later in the season.

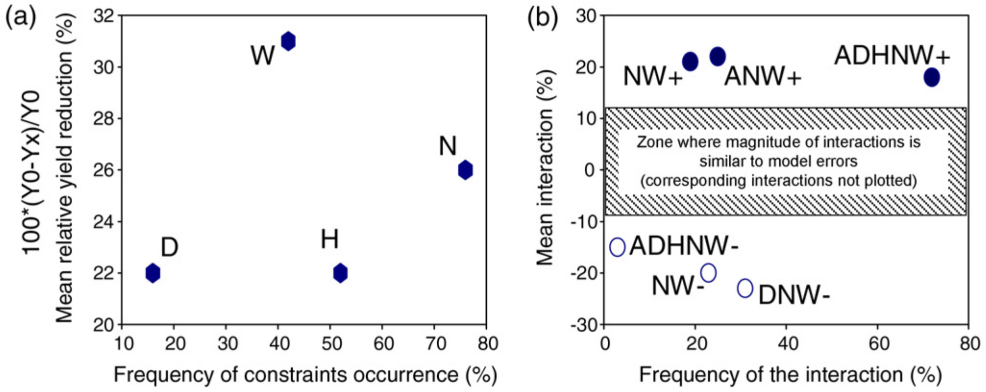

Fig. 8. Main yield constraints in Brazil (A: aluminium toxicity; D: plant density; H: weeds; N: nitrogen; W: water). Frequency of occurrence (*x*-axis) corresponds to the proportion of plots in which relative yield reduction was above 10%. Relative yield reductions (*y*-axis) are averaged over the plot sample, discarding plots with yield reduction below 10%. Impact of interactions between the constraints added to the model STICS. Main effects (a) and interactions between constraints (b). Interactions are the differences between overall effect of a set of constraints and sum of the main effects of each constraint in the set. Interactions are averaged separately for negative (− symbol: lower yield reduction than expected from the sum of the main effects) and positive cases (+ symbol: stronger yield reduction than expected from the sum of the main effects).

Adapted from Affholder et al. (2003).

5. Conclusion

The analysis of yield gaps in farmers' fields across different case studies of tropical family agriculture allowed a comparative understanding of their magnitude and causes. It provided insights into the factors at play in crop yield variations across the wide diversity of situations found between fields, often of the same farm. The analysis proved particularly helpful in showing that the share of yield variations due to crop management was greater or equal to the share of yield variations due to the main climatic drivers of crop production. It revealed similarities between contrasting agro-ecosystems, with relative actual-to-potential yields (Y_a/Y_W) fluctuating between 0.2 and 0.5, and a predominance of soil fertility, weed infestation and agronomic management as the factors that explain the yield gap. The use of best farmers' yields and boundary curves of observed yields against seasonal rainfall as reference for potential yields appeared to strongly underestimate yield gaps in our four case studies. A more satisfactory approach was the use of a relatively simple crop simulation model to calculate yield potentials (Y_W). The accuracy of the Y_W estimates depends highly on the cultivar-specific model parameters, and thus on the existence of experiments designed for estimating these parameters. Yet, even then crop modelling may underestimate yield gaps in the case of subsistence farming in which traditional, multi-purpose cultivars are still extensively used. For instance, there may be large room for yield improvement due to new market opportunities, if e.g. farmers shift from traditional to modern cultivars suited to respond to a growing market demand for grain. Alternatively, yield gaps could be calculated against simulated potential yields of hypothetical cultivars suited to market oriented farms in a certain region. Defining such hypothetical cultivars would require additional research. In any case, contributing to the sustainable intensification of family farms in the tropics will not only depend on ecologically sound technologies suited to tropical environments but also on the opportunity for subsistence farms to transform into market oriented farms.

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