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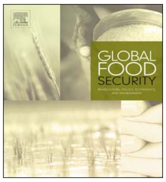

Can yield gap analysis be used to inform R & D prioritisation?

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ABSTRACT

The phrase “biggest bang for a buck” is associated with the policy making question that governments and development agencies face: “Where and which crops should receive highest priority for improving local and global food supply?”. A first step of prioritisation is to identify region x crop combinations for which high impact can be anticipated. We developed a new method for this prioritisation exercise and applied it to data from the Global Yield Gap and Water Productivity Atlas (GYGA). Our prioritisation distinguishes between two policy objectives (humanitarian and economic) and builds upon the relative yield gap and climate risk. Results of the prioritisation are presented and visualised in Google Earth.

1. Introduction

A number of recent studies have estimated the gap between potential yield and actual yield obtained in farmers' fields (e.g. Waddington et al., 2010; see van Ittersum et al., 2013 for a review of recent yield gap analyses). However, such studies have been criticised (Sumberg, 2012). Sumberg observed that in the yield gap analyses which he reviewed, “no indication is given how to move systematically from the identification of a gap to the development of specific policy prescriptions”. Sumberg observed that where possible interventions to close the yield gap are mentioned, these are in most cases “a set of broad responses around which there is already general agreement and which do not follow directly from the yield gap analysis”. According to Sumberg, yield gap analysis is used as “a simple and powerful policy framing device”, and “It brings an aura of scientific analysis and quantification and appears to be technically rooted. A large gap focuses the mind: surely something must and can be done!”.

Can yield gap analyses be more than just a framing device? We propose that the answer depends on the type of yield gap analysis. One type can be described as ‘broad scope, low detail on causes’, i.e. with a broad scope in terms of crops, large spatial coverage and less focus on identification of causes of yield gaps. A second type is ‘narrow scope, more detail’ with narrow focus (often just one crop), limited spatial coverage, and with much more detail on identification of causes for closing the yield gap. Examples of yield gap analyses in the ‘narrow scope, more detail’ category refer to specific crops, e.g. rice: Tanaka et al. (2015, 2013); wheat: Van Rees et al. (2014); maize: Tamene et al. (2015); and soybean: Grassini et al. (2015a). It is easier to derive more specific policy recommendations from such studies because they do provide information about the causes of yield gaps, which can include biophysical constraints such as abiotic/biotic stresses, poor land and crop management practices, socio-economic constraints such as limited access to financial services, and institutional or political constraints including market price. Once specific causes of yield gaps have been identified, the priorities follow directly from the analysis: priority must be given to addressing those factors contributing most to large yield gaps. Prioritisation can be further refined with information on which causes of yield gaps can more easily be resolved and which ones are very hard to resolve based upon available technologies and expected cost-benefit ratios.

Potentially the studies in the ‘narrow scope, more detail’ category can be useful for local action. However, such studies all use somewhat different methods and are restricted to a certain crop (or two) and one or a few regions making comparison among crops and regions difficult. The ‘broad scope low detail on causes’ category of yield gap analyses does not have these limitations, but one is left wondering if their role can be more than a framing device. The Global Yield Gap and Water Productivity Atlas (GYGA - www.yieldgap.org) explicitly mentions two policy questions that can be answered with yield gap analyses: (1) are production targets (for self-sufficiency or export) attainable on current land by increasing yields, or will additional area expansion be necessary? and (2) which parts in the world, which parts in a country and which crops should get priority for efforts to narrow the yield gap?

The first policy question has already been addressed in a number of

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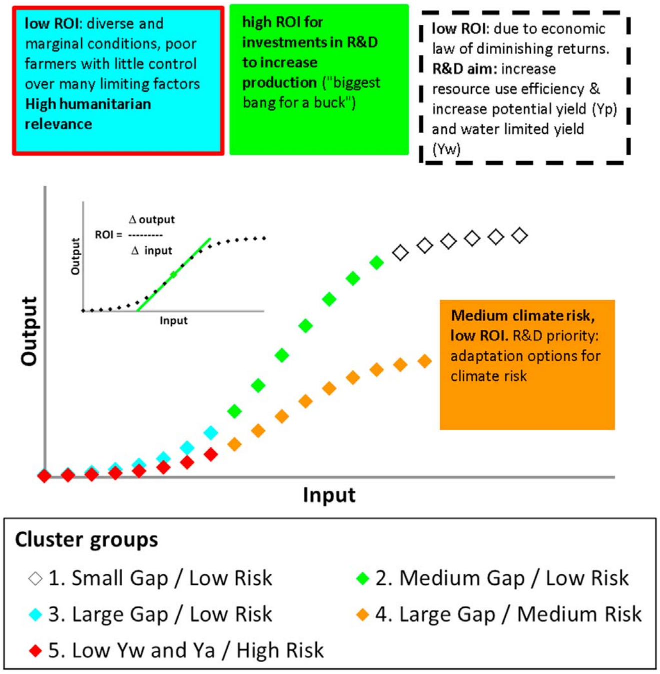

Fig. 1. Conceptual model for prioritisation. Top left inset shows how ROI is calculated, bottom legend shows the names of the 5 cluster groups. Coloured boxes briefly describe the five cluster groups; the description for groups 3 and 5 is merged in one box. Slope (=ROI) is low in the left and right, higher in the middle (orange) and highest in the green group. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

studies (Tilman et al., 2011; Aramburu Merlos et al., 2015; Van Oort et al., 2015; Marin et al., 2016). The second policy question has to date not been addressed. But it seems very relevant for international agencies and national governments to know where and with which crop the highest impact can be achieved from their investments in research and development. Or in popular terms, where and with which crop they can achieve “the biggest bang for a buck”. Here, we propose a method for deriving simple, first cut, prioritisation of R & D based on ‘broad scope, low detail on causes’ yield gap analyses from GYGA.

2. Conceptual framework

2.1. Prioritisation: economics, risk and humanitarian perspective

We present our conceptual model for prioritisation in Fig. 1, with 5 cluster groups, for which we expect different return on investment (ROI). As shown in the figure, ROI is the slope of the S-shaped input-output curves. Slope is highest in the middle part of the S-curves and lower in the left part and right part of the curves. We explain the causes and implications of these ROI differences in Section 2.1.1. In Fig. 1 we show two curves, one for lower climate risk and one for higher climate risk. We explain the causes and implications of climate risk for ROI and the research agenda in Section 2.1.2. Note that in Fig. 1 with inputs on the x-axis we refer not only to physical inputs such as water, labour and fertiliser, but also “institutional and information inputs” such as market access, well-functioning cooperatives and extension services. In Table 1 we present policy recommendations for the 5 cluster groups shown in figure 1.

2.1.1. Return on investment (ROI)

Return on investment ROI (=slope) in the left part of Fig. 1 is low. Here we find the farmers in marginal areas who face many constraints. As soon as input of one limiting resource is increased, leading to a small yield increase other resources become limiting, putting a low plateau to yield increase (Liebig's law of the minimum). In such cases one often finds that if multiple inputs are increased at the same time the yield increase is larger than when any one individual input is increased at a time (de Wit, 1992). But increasing multiple inputs at the same time often turns out to be difficult and this is why interventions are often less effective than aspired and more complex and costly to achieve (Fresco et al., 1994). Another issue for the marginal areas is that they often show large agro-ecological, social, infrastructural diversity and therefore require tailor made solutions for each particular area (Reece and Sumberg, 2003). The consequence of this is that science faces demand for a greater variety of technologies than it can feasibly develop (Settle and Garba, 2011; Sterk et al., 2013). Both the multitude of limiting resources and the large variability cause a low expected return on investment (ROI) for marginal areas. Slopes are steepest in the middle part of Fig. 1, indicating highest return on investment. These are the cases for which we may expect the “biggest bang for a buck”. By definition slope is steepest in the middle part, but we can see it is still steeper in the low risk than in the high risk curve – we come back to this point in Section 2.1.2. Slope and therefore ROI is low again in the right part of Fig. 1. The slope flattens off because yields approach their biophysical maximum. As a result of the economic law of diminishing returns it is a well-known phenomenon that crop yields reach an economic plateau at around 80% of the potential (Cassman et al., 2003; Grassini et al., 2013). While ROI on further investments is low in these sites, their high productivity renders them important from a global food perspective. For sites in the right part, R & D could focus on increasing the yield potential, increasing resource use efficiency and reducing environmental impacts.

Table 1
R & D recommendations for five groups identified by cluster analysis (Fig. 1).

Cluster group	R & D recommendation
1. Small gap/Low risk (white ◊)	Focus on increasing resource use efficiency and increasing potential yield or water limited yield.
2. Medium gap/Low risk (light green ◊)	“Biggest bang for a buck”. Most attractive from the economic perspective, as climate risk is small and expected return on investment (ROI) is largest. For governments/agencies seeking high impact in the short run, this is the group to focus on. Next step should be to identify where crops in this cluster group are located, conduct more detailed research on causes of yield gaps, promote good agricultural practices and improve institutions in the value chain.
3. Large gap/Low risk (light blue ◊)	High humanitarian relevance. This group has in the long run the highest potential for increasing crop yield. For governments/agencies seeking high impact in the long run, this is the group to focus on. The next step should be to investigate causes of yield gaps and possible solutions. No resources should be wasted on better understanding of the climate risk as climate risk is small.
4. Large gap/Medium risk (orange ◊)	High humanitarian relevance. Agricultural research and development (R & D) should focus on reducing climate risk. The next step could be to use crop growth models in a more diagnostic way to get a better understanding on the nature of the climate risk and options to reduce climate risk (such as shifting sowing dates, shorter duration varieties, water harvesting).
5. Low Yw and Ya/High risk (red ◊)	Same recommendation as group 4

2.1.2. Climate risk and ROI

In Fig. 1 we show two response curves, reflecting different degrees of climatic risk. Cropping systems with high yield potential typically exhibit low year-to-year yield variability and vice versa (Grassini et al., 2014). Therefore, harsh and variable climate generally limits maximum productivity and makes investment in agricultural inputs more risky. Regions with a high climatic risk have a lower ROI (compare the slope for the light green and orange points). The distinction between high risk and low risk is important not only from the perspective of where higher ROI is expected, but also for the research agenda. Where risk is large adaptation options to risk must be investigated. Crop growth models can be used in a more diagnostic way to get a better understanding on the nature of the climate risk and options to reduce climate risk (such as shifting sowing dates, shorter duration varieties, water harvesting), for example see Chapman (2008) and Heinemann et al. (2008), (2015). Where risk is low, no resources need to be wasted on investigating climate risks. Where risk is low and the gap large, research should focus on what other factors are limiting the actual yields (crop management, soil toxicities, biotic stresses such as mammals and weeds, plant diseases, etc.).

2.1.3. *Economic and humanitarian goals*

There is a tension between economic and humanitarian goals. From the economic perspective we would go for the “biggest bang for a buck”, i.e. where expected ROI is large (green points). From the humanitarian perspective we could be more inclined to invest in the large yield gap areas (light blue, red, orange) as these areas are likely to be food insecure. Another objection from the humanitarian perspective against the economic perspective is the argument that by supporting sites with medium yield gaps at the expense of sites with large yield gaps, marginal sites with large yield gaps are further marginalised (the rich get richer dynamics). Thus while our framework can help to provide more specific prescriptions of where to invest, it is ultimately this humanitarian or economic perspective that drives decision making.

2.2. *Yield gaps and climate risk*

2.2.1. *Source data*

We used data from the Global Yield Gap and Water Productivity Atlas (GYGA – www.yieldgap.org, (Grassini et al., 2015b; van Bussel et al., 2015; van Ittersum et al., 2013; Van Wart et al., 2015, 2013)). Project output data were downloaded on 2 November 2015. At the time of the download 5 crops were available (maize, millet, rice, sorghum and wheat) for 23 countries across the globe, both in developed and developing countries. The number of crops and countries is still growing as we are writing. Our objective at this stage is on methodology development, for which full global coverage is less critical.

Yield gaps in GYGA were quantified using local data on actual yields and crop growth simulation models to quantify potential and water-limited potential yields. Average yield (Ya) was defined as the long term average yield achieved by farmers in a given region under dominant management practices (sowing date, cultivar, and plant density) and soil properties. With regards to data quality, large discrepancies between official yield statistics and independent yield measurements have been found in African countries (e.g., Wairegi et al., 2010; Tittonel and GIller, 2013). Hence, whenever possible, we validated national statistics against yield estimates from other independent data sources (Grassini et al., 2015b). In irrigated systems, yield potential or potential yield (Yp) is the yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively. Therefore, crop growth is determined by solar radiation, temperature, atmospheric CO_2 concentration, and genetic characteristics. Yp is location specific because of the climate, but, in theory, not dependent on soil characteristics. Yp is used as benchmark for estimating yield gaps only for fully irrigated crops. For rainfed crops, water-limited yield potential (Yw) is the most relevant benchmark. Yw is defined similar as Yp, but crop growth is also limited by water supply, and hence influenced by soil type and field topography.

Effects of weather variability on simulated yields were quantified from interannual variation in yields simulated using a minimum of 10 years of weather data (but more if data were available). The finest spatial resolution is the so-called “buffer zone”, which is a zone of ca. 100 km radius around a weather station, located within an important area for crop production and deemed representative for crop production in a climate zone (Van Wart et al., 2013; Van Bussel et al., 2015). Thus if harvested area of a certain crop within a climate zone or within a buffer zone was small, or if no good weather data were available for that buffer zone, then no yield gap would be quantified for that crop x buffer zone combination – see van Bussel et al. (2015), Van Wart et al. (2013) and http://www.yieldgap.org/web/guest/methods-upscaling for quantitative details on site selection. This procedure led to a selection of crop x buffer zone combinations that would together cover at least 50% of the national crop harvested area. Selection was performed separately for irrigated and rainfed crops in countries where both water regimes were important for the same crop. These choices to reduce the number of crops and zones were based on considerations of data availability and number of crop x buffer zones to be evaluated. Separate analyses were conducted to identify what minimum number of buffer zones would be needed to allow for making accurate estimates of yield gaps at the national level (van Bussel et al., 2016, 2015; Van Wart et al., 2013). In Ghana for example seven buffer zones were selected, with one to five crops per buffer zone. Yield gaps in buffer zones across the 23 countries were highly variable, with actual yields ranging from 5% to 95% of potential production. This wide range of countries and data on distribution of crops within countries allows for benchmarking and it allows use for developing a spatially explicit prioritisation.

2.2.2. *Climate risk*

We used the coefficient of variation (CV) of annual simulated yields as a proxy for climate risk. Climate risk is a container term, which includes risk of drought, heat and cold, whereas none of the simulation models used in GYGA consider flooding. These risks obviously depend on not only weather, but also on management practices (sowing date, varietal choice, plant density), crop traits (e.g. maximum root depth and length of growing season), and soil properties (e.g. physical or chemical limits to maximum root depth and soil hydraulic properties). Sub-optimal sowing dates in rainfed crops can translate into high simulated climate risk (Wolf et al., 2015). We may also find large yield gaps in sites where the simulated climate risk is small (light blue points). For those sites, a manifold of other factors may cause the large yield gap (such as soil fertility, weeds, pests and diseases, labour availability, poor access to markets, etc.). We chose not to further investigate these causes at this stage. An outcome of the prioritisation developed here can be to pinpoint those areas where research into non-climatic causes of yield gaps is most direly needed.

2.3. *Clustering*

2.3.1. *Relative yield gap and CV*

We clustered GYGA data such that five cluster groups would match those shown in Fig. 1, our conceptual model. The clustering was based on relative yield gaps and climate risk. The relative yield gap was calculated as:

$$RelGap_{ir,c,b} = (\overline{Y}_{p,c,b} - \overline{Y}_{a,c,b,ir})/\overline{Y}_{p,c,b}=1-\overline{Y}_{a,c,b,ir}/\overline{Y}_{p,c,b} \tag{1}$$

$$RelGap_{rf,c,b} = (\overline{Y}_{w,c,b} - \overline{Y}_{a,c,b,rf})/\overline{Y}_{w,c,b}=1-\overline{Y}_{w,c,b,rf}/\overline{Y}_{p,c,b} \tag{2}$$

where $RelGap_{ir,c,b}$ is the relative yield gap for irrigated (*ir*) crops, for crop *c* (5 crops) in buffer zone *b* and $RelGap_{rf,c,b}$ is the same for rainfed (*rf*) crops. $\overline{Y}_{p,c,b}$ is the long term average potential (*p*) yield for crop *c* in buffer zone *b* used as the benchmark in irrigated systems,$\overline{Y}_{w,c,b}$ is the is the long term average water limited (*w*) yield used as the benchmark in rainfed systems. $\overline{Y}_{a,c,b,ir}$ and $\overline{Y}_{a,c,b,rf}$ are the long term average actual yield for crop *c* for farmers in buffer zone *b* for irrigated and rainfed systems respectively. All yields reported are yields in fresh matter, moisture contents can be found in www.yieldgap.org; for the five crops considered here moisture contents range from 13.5% (wheat) to 15.5% (maize).

We used the coefficient of variation of simulated potential yield $CV(Y_{p,c,b})$ and the coefficient of variation of simulated water limited yield $CV(Y_{w,c,b})$ as proxies for climate risk. $CV(Y_{p,c,b})$ was calculated as:

$$CV(Y_{p,c,b}) = 100\% \times STDEV(Y_{p,c,b,y}) / \overline{Y}_{p,c,b} \tag{3}$$

where $STDEV$ measures variation in potential yield over the simulated years (y) and where $\overline{Y}_{p,c,b}$ is the already mentioned long term average potential (p) yield for crop c in buffer zone b. A similar equation but with water limited yield Y_w was applied in rainfed systems. Note that both $RelGap$ and CV are normalised by Y_p or Y_w.

2.3.2. Relative and absolute yield gaps

The use of relative yield gaps (=normalisation) has methodological advantages and disadvantages. Advantages are that normalisation makes it possible to compare crops with different absolute yield gaps and regions with different crops. A disadvantage of using relative yield gaps is that it may lead to prioritisation of low impact crops or regions, i.e. crops with high ROI but small harvested area, or crops with high ROI but small absolute yield gap. We therefore also report absolute yield gaps and we also report on what prioritisation follows when accounting for the absolute yield gap and crop area. We define potential production gain as how much production in megatons (MT) can increase, based on potential yield Y_p (for irrigated systems) or water limited yield Y_w (for rainfed systems), crop area and an economic multiplier to Y_p or Y_w (0.8) because yields often plateau at 80% of the potential. Potential production gain for crop c was calculated as:

$$\text{Pot. ProductionGain}_c = Area_{ir,c} \times (0.\,8 \times \overline{Y}_{p,c} - \overline{Y}_{a,c,ir}) + Area_{rf,c} \times (0.\,8 \times \overline{Y}_{w,c} - \overline{Y}_{a,c,rf}) \tag{4}$$

where $Area_{ir,c}$ and $Area_{rf,c}$ are the irrigated (ir) and rainfed (rf) area, $\overline{Y}_{p,c}$ and $\overline{Y}_{w,c}$ are the potential and water limited yield, long term average, for crop c and $\overline{Y}_{a,c,ir}$ and $\overline{Y}_{a,c,rf}$ are the long term average yields for the crop c in irrigated and rainfed systems.

On first sight, potential production gain offers the more balanced picture compared with prioritisation based on relative yield gaps and climate risk, because the potential production gain approach takes into account crop areas and the absolute yield gap. A potential drawback is that it is a static indicator in the sense that it is calculated with current crop areas (or actually: with crop areas based on SPAM2005 (You et al., 2014), thus already 10 years old). If the harvested area of a certain crop has strongly expanded since 2005, more than for other crops, then the current potential production gain of this crop would be underestimated by using SPAM2005 harvested areas. Particular crops in the high ROI cluster might be prioritised for area expansion based on their high ROI (without weighting by crop area) which would increase their potential production gain. For the policy making question on where and for which crops to support area expansion, the relative yield gaps also seem to add useful information. This is why we present a prioritisation based on both potential production gains and on relative yield gaps/climate risk (Table 1).

2.3.3. Clustering method

A hierarchical agglomerative clustering (Kettenring, 2006) following Ward's method (Ward, 1963) was performed on 634 data points using two variables (relative yield gap and CV). R version 3.2.2 was used for this analysis (R-Core-Team, 2015). The result was the identification of 5 distinct clusters differing in relative yield gap and CV. R was also used to generate pie charts of this clustering per crop and site for visualisation in Google Earth. Pie chart size was chosen purely on cartographic (aesthetic) criteria, pie chart size does not reflect the size of the simulated area. Also segments in the pie do not reflect crop areas, we applied equal segment sizes for each crop, also for aesthetic reasons. Readers can download the kmz file and visualise it in Google Earth. The data plus a brief how-to can be downloaded from www.yieldgap.org/web/guest/download_data.

Table 2
Mean actual yield, potential yied or water-limited yield and its CV, and yield gaps across all the dataset.

	Irrigated			Rainfed				
	Maize	Rice	Wheat	Maize	Millet	Rice	Sorghum	Wheat
Number of buffer zones	73	21	14	161	82	29	85	169
Actual yield (t/ha)[a]	10.3	3.4	2.2	3.2	0.9	2.0	1.1	3.0
Potential yield (t/ha)[a]	15.2	9.0	5.5	9.3	3.4	6.3	5.8	5.8
Climate Risk (CV, %)	9	4	14	37	41	33	34	41
Absolute yield gap (t/ha)	4.9	5.5	3.3	6.1	2.5	4.3	4.7	2.8
Relative yield gap	0.31	0.62	0.59	0.65	0.69	0.67	0.77	0.48

[a] Yields reported are in fresh matter, i.e. incl 13.5–15.5% moisture.

3. Results

3.1. Description of the data

The analysis included 23 countries with yield gaps ranging from 3% to 97%, CV ranging from 1% to 152% and countries ranging from very rich to very poor. Table A1 in Appendix A shows the number of buffer zones disaggregated by country, crop, production system, and gross national income (GNI) per capita. Richer countries generally have smaller relative yield gaps (Table A1: countries with a high gross national income (GNI) per capita have an for maize average relative yield gap of 0.32 (range 0.15–0.51) and 'low GNI per capita' countries have for maize an average yield gap of 0.71 (range 0.59–0.75). On average over buffer zones in each crop and production system, irrigated systems have higher actual yields, higher potential yields and lower climate risk than rainfed systems (Table 2). Irrigated maize had the highest actual yield and highest potential yield, followed by irrigated rice and rainfed maize (Table 2). Irrigated maize has a much smaller relative yield gap (0.31) than irrigated rice (0.62) and irrigated wheat (0.59). The reason for this large relative yield gap in irrigated rice and wheat is likely due to the relationship between yield gaps and countries wealth: irrigated rice and irrigated wheat in our dataset are found in the lower income countries which generally have larger yield gaps while most irrigated maize in our dataset was found in the higher income countries which generally have smaller yield gaps. Rainfed millet had the lowest actual yield, lowest potential yield, largest relative yield gap and lowest absolute yield gap.

3.2. Cluster analysis

Five distinct clusters were identified (Fig. 2a). Fig. 2a shows both cluster 1 (white) and cluster 5 (red) have a small relative yield gap. The key difference is that cluster 1 has high actual yields and high potential or water limited yields while cluster 5 has low actual yields and low water limited yields (Fig. 2c and d). Based on this and on the difference in CV was we placed these points in two separate clusters and refer to cluster 5 as "Low Yw and Ya/High Risk".

3.3. Prioritisation by potential production gains in Africa

In Africa only 9% of all crop x buffer zone combinations are in the cluster with high expected ROI (Table 3). The high ROI cluster is dominated by irrigated crops (rice: 33%, wheat: 12%, see Table 3 last

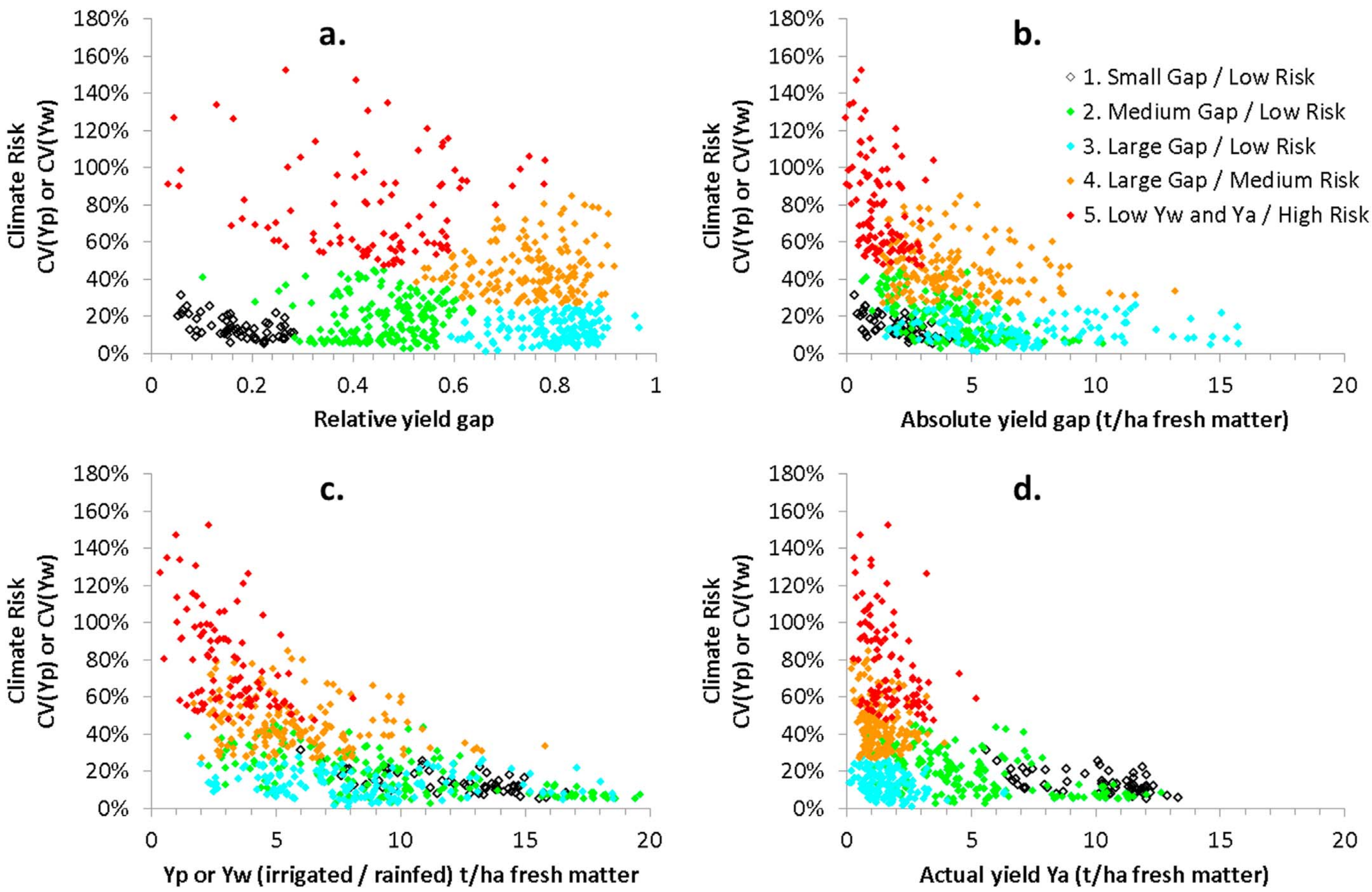

Fig. 2. Cluster analysis. (a) climate risk vs relative yield gap. Clustering was based on this figure. Figures b–d show the same clusters but with absolute yield gap (b), benchmark yield Y_p or Y_w (c) and actual yields (d) on the x-axis. Each data point represents one crop x buffer zone combination. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Table 3
Occurrence of the medium gap x low risk group for five crops in the African countries.

	Clusters per buffer zone in Africa			Total harvested area (1000 ha)[b] per crop in the 12 GYGA countries in Africa	Within Medium gap x low risk cluster 2: frequency of buffer zones per crop
	Medium gap x low risk cluster 2	Other 4 cluster groups	Total buffer zones		
Irrigated rice	11 (52%)	10 (48%)	21 (100%)	418 (1%)	33%
Irrigated wheat	4 (57%)	3 (43%)	7 (100%)	145 (0%)	12%
Rainfed maize	1 (1%)	104 (99%)	105 (100%)	12,877 (27%)	3%
Rainfed millet	6 (7%)	76 (93%)	82 (100%)	14,810 (31%)	18%
Rainfed rice[a]	8 (28%)	21 (72%)	29 (100%)	3393 (7%)	24%
Rainfed sorghum	2 (2%)	83 (98%)	85 (100%)	14,703 (30%)	6%
Rainfed wheat	1 (3%)	37 (97%)	38 (100%)	2022 (4%)	3%
Total	33 (9%)	334 (91%)	367 (100%)	48,369 (100%)	100%

[a] Rainfed rice was modelled as rainfed lowland and rainfed upland, from which the weighted average rainfed rice yield was calculated. Rainfed lowland yields caused the high % for medium gap x low risk thanks to access to shallow groundwater.

[b] Crop areas in GYGA were at the time of data download based on SPAM2005 (You et al., 2014).

column) and rainfed rice (24%). Rainfed rice in GYGA is the (area weighted) average of rainfed lowland rice and rainfed upland rice. Rainfed lowland rice has smaller relative yield gaps and smaller climate risk because it benefits from shallow groundwater. Together these irrigated and groundwater-fed groups cover 69% of the high ROI cluster but they represent only 8% of total crop area (Table 3). Therefore investments in rice and wheat risk having limited impact, because of the limited crop area. Rainfed millet has some more buffer zones in the high ROI cluster than maize and sorghum (7% vs 1% and 2%) and has a relatively large area (31%), but due to the low absolute yield gap (Table 2), investments in millet may have limited impact in terms of potential production gain.

The low anticipated impact for the high ROI crops is confirmed in Table 4. Based on the full dataset, the outcome is that greatest impact (potential production gain) can be achieved with rainfed maize and rainfed sorghum (Table 4), suggesting these crops should be prioritised. Use of the high ROI subset would lead to a quite different prioritisation, showing that largest production gains can be obtained with rainfed millet, rainfed maize and irrigated rice. A grim picture emerges if we consider the ‘high ROI’ cluster 2 as being the subset for which production gains can more easily be obtained. The ‘easy’ production gain of 860 MT (Table 5) in the GYGA African countries represents only 0.6% of the total potential production gain of 155267 MT (Table 4). The high frequency of cluster 3 (large gap, low risk), which we will see in the next section, offers a more hopeful image, indicating that many crop x buffer zone combinations in Africa have potential for high impact in the long run.

Table 4
Potential production gain (MT) from the full dataset of the African countries.

	Burkina Faso	Ethiopia	Ghana	Kenya	Mali	Morocco	Niger	Nigeria	Tanzania	Tunisia	Uganda	Zambia	Total	%
Irrigated rice	65		85		843			107	351				1451	1%
Irrigated wheat										387			387	0%
Rainfed maize	1487	13,398	3947	6275	2305			25,256	9218		3026	4108	69,020	44%
Rainfed millet	2160	929	509	215	2754		2015	4684	246		535	189	14,235	9%
Rainfed rice*	84		404		310			6936	2108		68		9910	6%
Rainfed sorghum	4557	4734	1518	460	3897		5642	30,957	1009		783		53,556	34%
Rainfed wheat		5438		203		122			98	847			6708	4%
Total	8353	24,498	6464	7153	10,108	122	7656	67,940	13,029	1233	4413	4297	155,267	100%

Note these calculations are based on crop areas (based on SPAM2005) and long term average yield gaps (approximately 1998–2012) as reported in GYGA. Since 2005 crop areas and actual yields have increased substantially according to FAOSTAT. The numbers in this table are therefore best interpreted in terms of looking at relative differences between countries and crops and not too much in absolute sense. What we can see from the table is that largest production gains can be obtained from rainfed maize and from rainfed sorghum.

3.4. Prioritisation: visualisation in google earth

In this section we zoom out to the continental level and zoom in within countries. Figs. 3–5 below show the relative yield gap x risk categories spatially for Europe, Africa and South America. In Europe (Fig. 3) the dataset contains yield gap analyses for the Netherlands, Denmark, Germany, Poland and Spain, for maize and wheat (Table A1). In the Netherlands and Germany all buffer zones are in cluster group 1 (white, Small gap/Low Risk). The policy recommendations for this cluster group (Table 1) are that for the Netherlands (wheat) and Germany (wheat and maize), agricultural R & D should focus on increasing resource use efficiency increasing the yield ceiling and reducing environmental impact. Actually this is what governments in these countries have been doing already in recent decades. For example in the Netherlands government has been introducing environmental legislation (leading to increasing resource use efficiency), government is promoting precision farming (www.precisielandbouw.eu/) and private sector breeders are raising the yield plateau (Rijk et al., 2013). In Poland (wheat and maize) almost all buffer zones are in the green category where a high economic return on investment for closing the yield gap is expected (Fig. 1). In the south east of Poland, three locations have a large gap and small risk. In Spain (wheat and maize), all five cluster groups are found. Therefore in Spain, more than in other European countries, it is worthwhile to zoom in and develop separate R & D targets for the different crops and locations.

In Africa, almost all stations are in the large gap groups (3 light blue/4 orange) or in the high climate risk group (5 red). Thus from the humanitarian perspective it is clear that agricultural investments should take place in Africa. Amongst these three categories, impact will probably most easily be obtained in the light blue (large gap, low risk) cluster. The nice thing of spatially explicit analysis is that one can zoom in to identify where and with which crops these light blue cases are found. Likewise it is possible to zoom in and identify those rare (green) crop x buffer zone combinations with high expected ROI. As we discussed in the previous section, this high ROI cluster is dominated by irrigated and groundwater-fed crops (Table 3).

At the time of data download only one crop (irrigated maize) was simulated for the USA and only two crops (maize, wheat) were simulated for Brazil and Argentina in South America. In South America (Fig. 5), most buffer zones are in category 2 (medium gap, low risk). Two regions have large climate risk: in the North East of Brazil (Monte Santo and Cipó) and in the very South of Brazil. For these sites it will be of interest to further investigate the cause of high climate risk.

4. Discussion

We have shown that it is possible to develop spatially and crop explicit R & D policy recommendations based on the results of the GYGA project. Although the recommendations are inevitably still quite general, they are more sophisticated than Sumberg's (2012) suggestion that "for those wanting to draw attention to the need for further investment in African agriculture, the motivation is to construct the largest gap possible." Our analysis also identified a number of uncertainties and relevant follow-up questions. We discuss the most important ones below.

4.1. Uncertainties due to categorisations

Any representation of continuous phenomena into categories introduces some uncertainty. In this paper, two sources of uncertainty were introduced. Firstly, regarding the categorisation into rainfed/irrigated, we are aware of the phenomenon of 'deficit irrigation' where irrigation is applied but not enough to completely fulfil crop water requirements. Therefore recently a third category has been added: Partially-irrigated crops. In the current paper this category is not present, because for the dataset compiled and used here, this category was not yet available and accordingly no actual yield and irrigation scheduling data were collected. For the future, uncertainty will be reduced thanks to the addition of this new "partially irrigated" category. Secondly, clustering is more uncertain for data points in Figs. 1 and 2 at the boundary between two clusters and

Table 5
Potential production gain (MT) in buffer zones in the African countries, with high expected return on investment.

	Burkina Faso	Ethiopia	Ghana	Kenya	Mali	Morocco	Niger	Nigeria	Tanzania	Tunisia	Uganda	Zambia	Total	%
Irrigated rice	0.4		3		179		0.2	8					190	22%
Irrigated wheat													0	0%
Rainfed maize											197		197	23%
Rainfed millet		42					0.0	361			11		414	48%
Rainfed rice*					52						6		58	7%
Rainfed sorghum								0.0			0.1		0	0%
Rainfed wheat				0.4									0	0%
Total	0.4	42	3	0.4	231	0.0	0.2	369	0.0	0.0	215	0.0	860	100%

Note these numbers are based on reported crop areas per 100 km radius buffer zone around weather stations and not considering crop areas outside these buffer zones. In reality potential production gains will therefore be higher. The numbers in this table are therefore best interpreted in terms of looking at relative differences between countries and crops and not too much in absolute sense. What we can see from the table is that largest production gains can be obtained from rainfed millet, rainfed maize and irrigated rice.

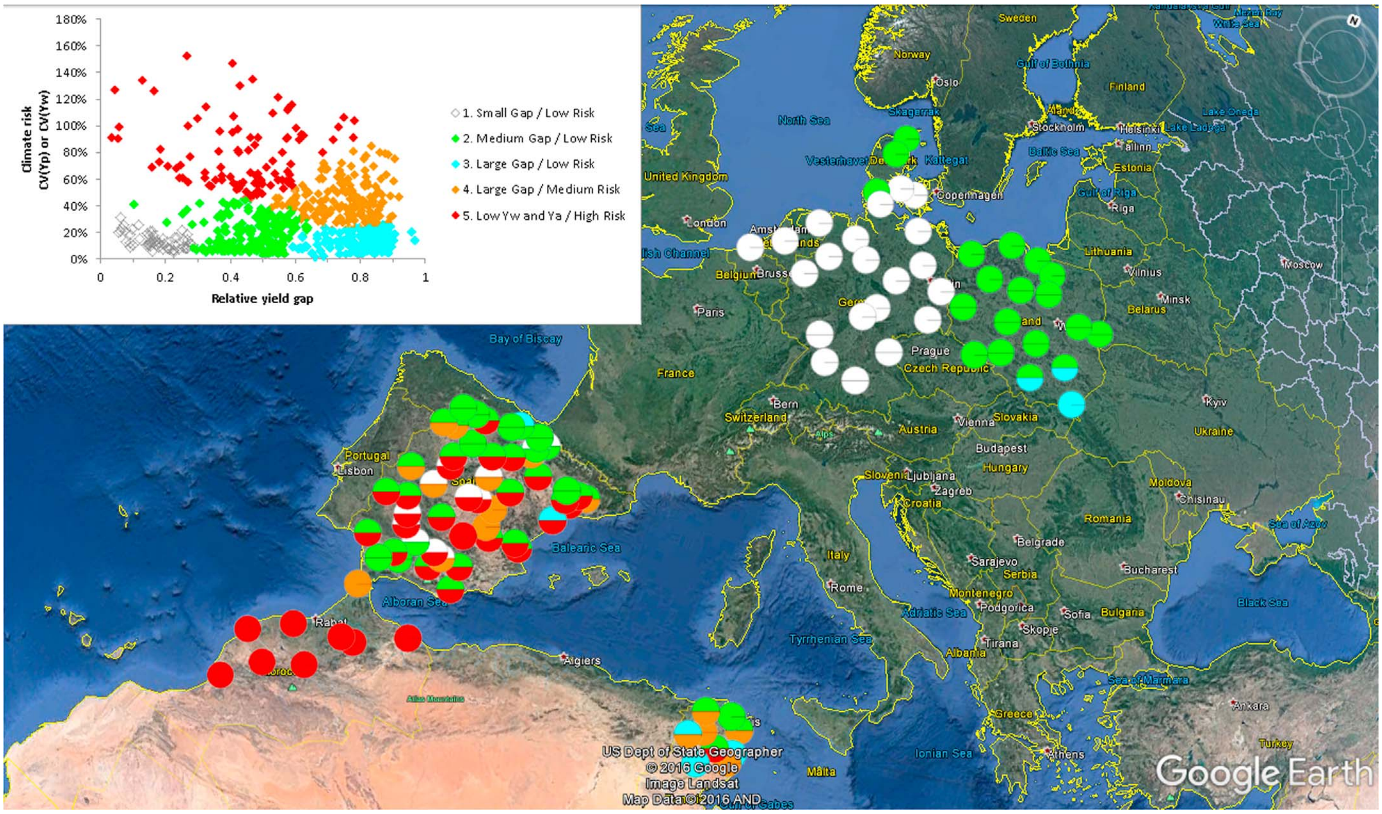

Fig. 3. Clustering in Europe and North Africa. Visualisation in Google Earth. All five cluster groups are found in Europe. The top inset shows the legend for the clusters and is identical to Fig. 2a of this paper.

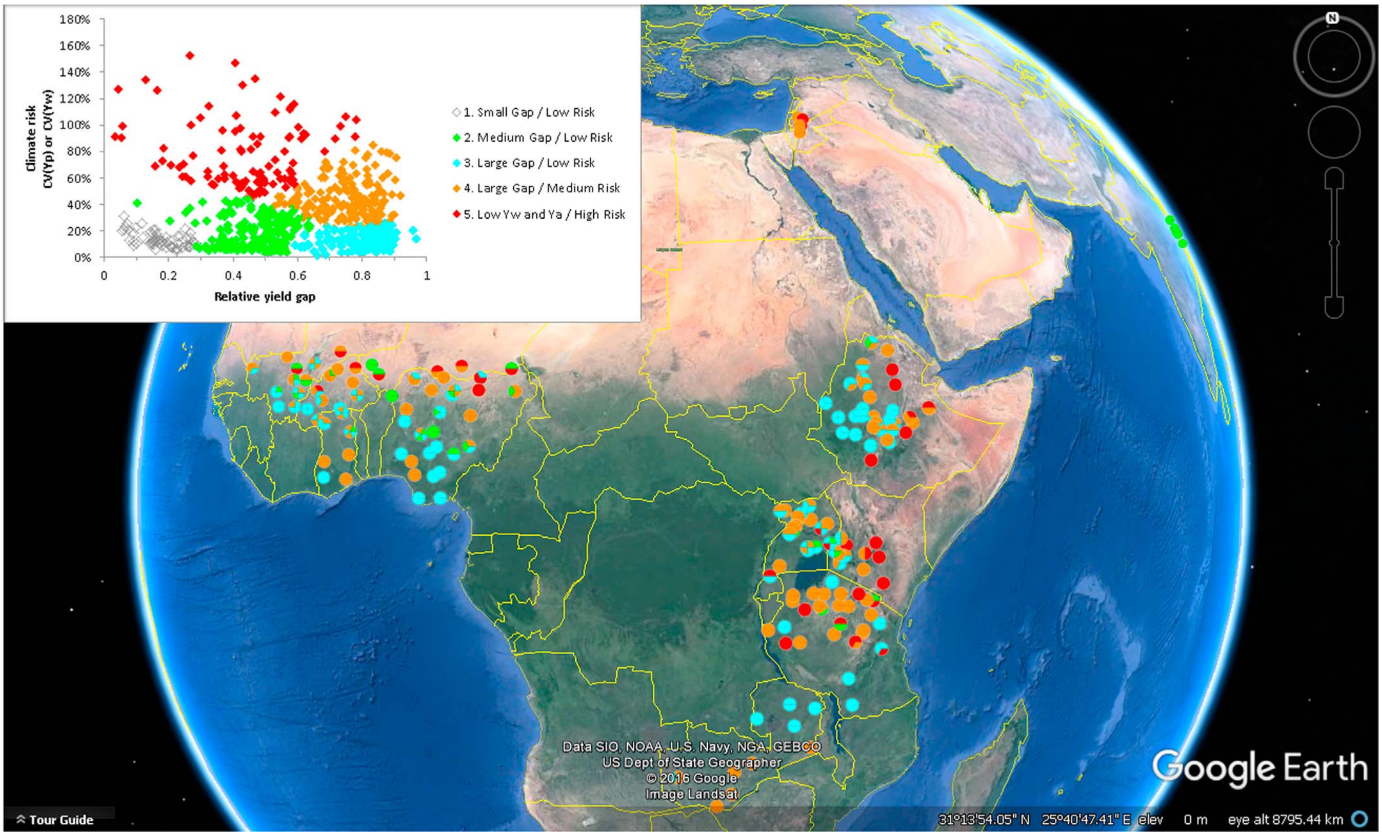

Fig. 4. Clustering in Africa. Visualisation in Google Earth. Four out of five cluster groups are found in Africa, none of the crop x buffer zone combinations was in the white cluster (1. Small gap/Low Risk). The top inset shows the legend for the clusters and is identical to Fig. 2a of this paper.

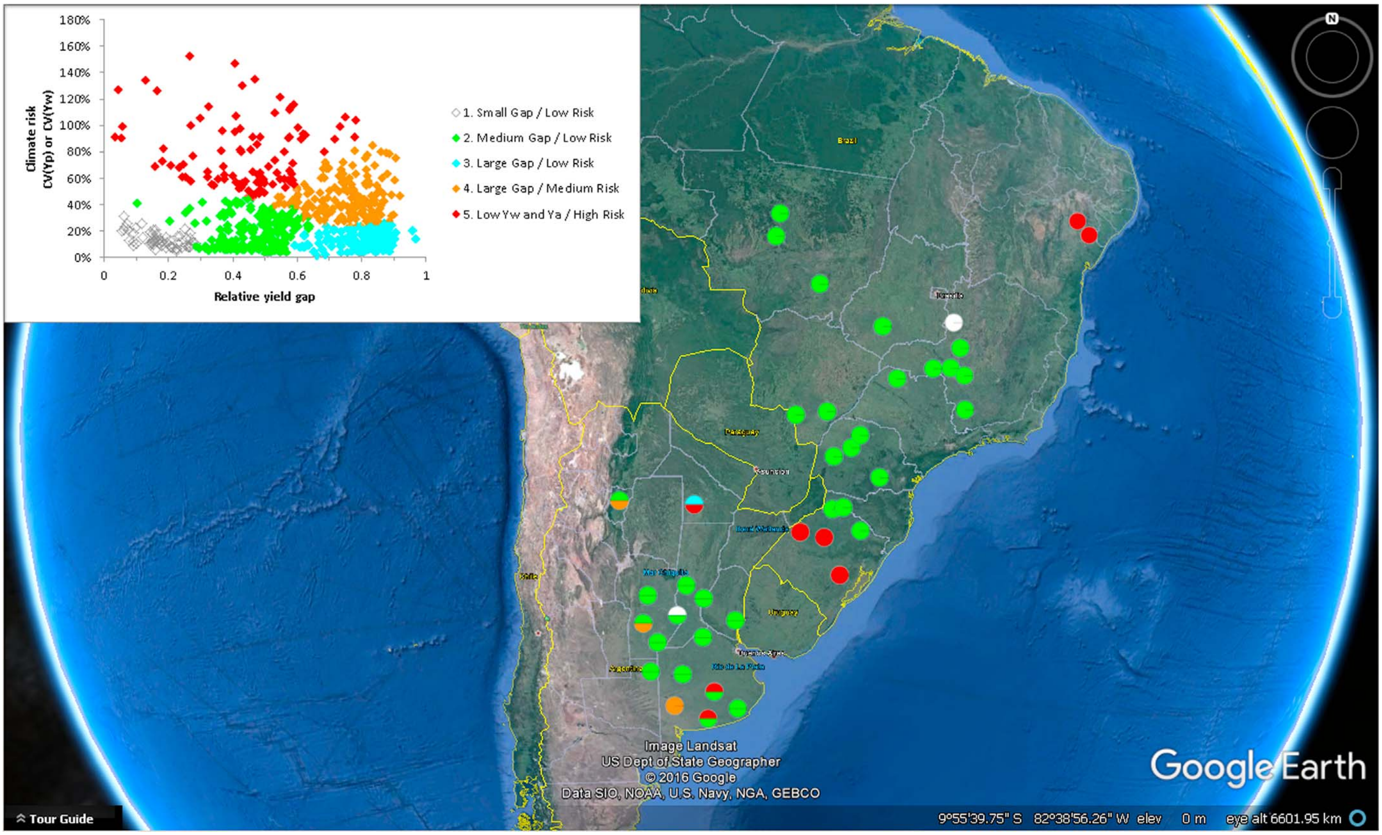

Fig. 5. Clustering in South America. Visualisation in Google Earth. All five out of five cluster groups are found in South America, most clusters are in the high ROI cluster (green). The top inset shows the legend for the clusters and is identical to Fig. 2a of this paper. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

uncertainty exists about the delineation of the cluster boundaries. We did not include detailed economic analyses to calculate ROI per site and per crop. As a result, there is no objective scientific justification for the threshold between cluster groups in Fig. 2 other than that the clustering intuitively makes sense and is consistent with our conceptual model. The whole idea of prioritisation is to first, using limited R & D resources, identify which sites and crops that should get priority and then spend most R & D funds on yield gap closure in prioritised sites/crops. Choosing between spending much more R & D funding on developing a more precise delineation of the cluster groups and keeping things simple but roughly right, we opted for the later. Our objective was to provide a simple, first cut, prioritisation of R & D.

4.2. *Should crop area be used for prioritisation?*

The potential production gain approach which does account for crop area led to prioritisation of maize and sorghum in Africa. The relative yield gap approach (without weighting by crop area or absolute yield gap) led to prioritisation of maize, rice and millet in Africa and prioritisation of irrigated sites in Africa. The relative yield gap approach may prioritise crops with limited crop area and therefore limited impact on food security. That is unless area of these crops is greatly expanded, but we did not investigate potential for expansion, see Section 4.3 below). The potential production gain approach may favour crops with large area but for which expected ROI is low. For these crops, expected production gains will be much costlier to achieve. There are also concerns about increasing homogeneity in global food supplies and the implications for food security (Khoury et al., 2014). Prioritisation based on potential production gain risks accelerating this process, because with potential production gain, crops with large area will in most cases show up has having high impact (maize and sorghum in Africa). If these two crops were to be prioritised their crop areas would become even larger, leading to further homogenisation. One contribution of this paper is that it quantitatively shows that the question of whether or not to weigh by crop area is not trivial. Two important follow up questions for further research are: (1) Should crop area be used for prioritisation? And (2) How to factor in the possible objective of diversification into our prioritisation framework?

4.3. *Irrigation in Africa*

Our analysis revealed that in Africa the ‘high ROI’ (medium relative yield gap, low risk) cluster was dominated by irrigated crops. This raises the question whether further intensification in existing irrigated systems is possible through double or triple cropping (van Oort et al., 2016). For the non-irrigated sites it is important to further investigate the potential of developing irrigation (Altchenko and Villholth, 2015; Windmeijer and Andriesse, 1993; You et al., 2011). When developing new irrigation sites it is important to do so in ways that do not create conflict over limited water resources (Dessalegn and Merrey, 2015) and avoid common causes of failure of such projects (Djagba et al., 2014; Rodenburg et al., 2014). The experience in many parts of Asia has shown that unlimited groundwater pumping risks mining groundwater levels at the expense of future generations. In Africa, groundwater pumping is slowly but steadily taking off (Pavelic et al., 2013; Villholth, 2013) and groundwater overexploitation is, at a large scale, not yet a problem in Africa (Richey et al., 2015). The important follow up question is: Can African policy makers with the support of hydrologists and local stakeholders design and enforce fair groundwater policies before the pumping revolution really takes off, rather than trying to solve problems once the damage has been done?

4.4. *Economics*

We are well aware that our economic perspective here (Fig. 1) is a gross simplification. All things being equal our premise of highest ROI for medium gaps (Fig. 1) is true. But in reality things are not equal. Other variables such as distance to market, market prices, strength of institutions including extension services, harvested area and many more variables can matter a great deal. Hopefully other researchers can use outputs of yield gap analyses in combination with ancillary variables to develop more accurate prioritisations. Likewise, our humanitarian perspective is also a simplification of reality. We did for example not consider the role of livestock and off-farm incomes (Frelat et al., 2016). It is for example not unthinkable that farmers with a good off-farm income have less time to spend on weeding, bird and rodent control, resulting in a larger yield gap while a poorer farmer with no or much lower off-farm income will have less choice and spend more time on the land to increase his/her yield. In this example, does our humanitarian perspective of giving priority to the large yield gap farmer still hold? Thus many nuances are possible and can be used to enrich the prioritisation. The underlying yield gap data and clustering presented here can act as a useful core dataset for more interdisciplinary analyses into causes of yield gaps and options to narrow them.

5. Conclusions

We have shown that it is possible to develop a spatially explicit, crop specific and climate specific prioritisation based strictly on the results of the Global Yield Gap and Water Productivity Atlas. Based on the policy objective (economic or humanitarian) and a clustering based on two criteria (relative yield gap and climate risk), different recommendations for research and development can be given. The visualisation in Google Earth using coloured piecharts allows for zooming in and out on different parts of the world. While it was shown to be possible to develop a prioritisation, the recommendations remain general. We consider this a first step towards more refined prioritisations. The clustering developed here can be used in the future as one core dataset together with ancillary data on biophysical and socio-economic causes of yield gaps to develop more specific policy making recommendations.

Downloads

The GYGA project has a user friendly online atlas accessible at www.yieldgap.org. At the time of writing, the spatial visualisation developed in this paper was not yet integrated in this atlas. Readers can download the kmz file and visualise it in Google Earth. The data plus a brief 'how-to' can be downloaded from www.yieldgap.org/web/guest/download_data.

Acknowledgements

We acknowledge the contribution from members of the GYGA project in terms of actual yield data, cropping systems information and crop model simulations. The vision presented here does not necessarily reflect the vision of other project members on use of yield gap analyses for prioritisation.

Appendix A

See Table A1.

Table A.1
Number of buffer zones disaggregated by country, crop, production system, and gross national income (GNI) per capita.

	Irrigated maize	Irrigated rice	Irrigated wheat	Rainfed maize	Rainfed millet	Rainfed rice	Rainfed sorghum	Rainfed wheat	Grand total	GNI per capita (US $/year)	Mean relative yield gap	Mean CV
High-income group												
Argentina				15				16	31	14,560	0.45	0.32
Australia								22	22	64,680	0.51	0.37
Denmark								5	5	61,310	0.20	0.27
Germany				6				13	19	47,640	0.15	0.17
Netherlands								3	3	51,210	0.21	0.09
Poland				10				17	27	13,730	0.51	0.19
Spain	47							50	97	29,940	0.41	0.30
USA	21								21	55,200	0.15	0.14
Upper-middle-income group												
Brazil				25					25	11,760	0.47	0.27
Jordan								5	5	5160	0.60	0.68
Tunisia			7					6	13	4210	0.67	0.40
Lower-middle-income group												
Bangladesh	5		7						12	1080	0.53	0.08
Ghana		2		7	3	2	3		17	1620	0.80	0.26
Kenya				8	10		11	5	34	1280	0.65	0.57
Morocco								9	9	3020	0.54	0.84
Nigeria		6		16	11	8	15		56	2950	0.74	0.33
Zambia				11	5	2			18	1760	0.83	0.34
Low-income group												
Burkina Faso		3		7	10	2	9		31	710	0.75	0.34
Ethiopia				24	13		19	12	68	550	0.71	0.33
Mali		4		6	8	5	8		31	720	0.72	0.32
Niger		4			4		2		10	430	0.59	0.58
Tanzania		2		13	8	4	4	6	37	930	0.71	0.45
Uganda				13	10	6	14		43	660	0.74	0.29
Total	73	21	14	161	82	29	85	169	634			

*GNI per capita in 2014 from https://en.wikipedia.org/wiki/List_of_countries_by_GNI_%28nominal,_Atlas_method%29_per_capita

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