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ABSTRACT

Micronutrient malnutrition, also known as hidden hunger, affects two billion people worldwide. In recent years, the global challenge of reducing hidden hunger and hence improving related health outcomes through agricultural interventions has received much attention. One potential solution is biofortification—the process of breeding and delivering staple food crops with higher micronutrient content. Biofortification could prove to be a cost-effective and sustainable strategy, especially in rural areas of many developing countries where production and consumption of staple crops is high and high micronutrient deficiency rates are rampant. The aim of this paper is to develop and implement country-crop-micronutrient–specific biofortification prioritization indices (BPIs) that will rank countries according to their suitability for investment in biofortification interventions to be used by various stakeholders with differing objectives. BPIs combine subindices for production, consumption, and micronutrient deficiency, using country-level crop production and consumption data primarily from the Food and Agriculture Organization (FAO) of the United Nations and iron, zinc, and vitamin A deficiency data from the World Health Organization (WHO). BPIs are calculated for seven staple crops that have been developed and for 127 countries in Africa, Asia, and Latin America and the Caribbean. BPIs should not be used as a one-stop shop for making decisions on biofortification investment decisions because they have several limitations. As they are currently calculated, BPIs do not explicitly take cost-effectiveness into account, neither do they allow for a subnational analysis. Future research will address these shortcomings. For now, the BPIs presented in this paper are useful tools for highlighting those countries that may benefit from significant reductions in micronutrient deficiency through biofortification of staple crops.

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CONTENTS

I. INTRODUCTION

Micronutrient malnutrition affects two billion people worldwide. Also known as hidden hunger, micronutrient malnutrition results from poor quality diets, characterized by a high intake of staple foods, such as rice and maize, and low consumption of micronutrient-rich foods, such as fruits and vegetables. Hidden hunger particularly affects populations living in poverty that often do not have the means to grow or purchase more expensive micronutrient-rich foods. Hidden hunger contributes significantly to the global disease burden of children by limiting proper cognitive development, impairing physical development, and increasing susceptibility to infectious diseases. These health issues can have long-term effects on an individual's livelihood, as they substantially curtail one's ability to capitalize on economic opportunities (Bryce et al. 2003; Alderman, Hoddinott, and Kinsey 2006).

In recent years, the global challenge of reducing hidden hunger, and hence improving related health outcomes, through agricultural interventions has received much attention (see e.g., Paarlbeerg 2012). One potential solution is biofortification—the process of breeding and delivering staple food crops with higher micronutrient content (Qaim, Stein, and Meenakshi 2007; Bouis et al. 2011; Saltzman et al. 2013). Biofortification could prove to be a cost-effective and sustainable strategy for alleviating micronutrient deficiency in rural areas of developing countries where the majority of the poor households' diets are comprised of staple foods and where access to food supplements and commercially marketed fortified foods is limited. Since 2003, breeders across the Consultative Group on International Agricultural Research (CGIAR) have been working to develop varieties of seven staple crops (cassava, maize, sweet potato, beans, pearl millet, rice, and wheat) that contain significant levels of bioavailable, critical micronutrients. The micronutrients of focus are vitamin A, iron, and zinc, which are—apart from iodine that can be fairly easily addressed by the iodization of table salt—recognized by the international nutrition community as most limiting in diets (Black et al. 2013). Interventions are planned or underway to adapt and multiply planting materials of these varieties and deliver them to rural households in Asia (Bangladesh, India, and Pakistan), Africa (Mozambique, Nigeria, Rwanda, Uganda, and Zambia), and Latin America and the Caribbean (LAC) (Bolivia, Brazil, Colombia, Haiti, Honduras, Guatemala, Nicaragua, and Panama).

Existing evidence suggests that biofortification is an efficacious and cost-effective strategy for alleviating micronutrient deficiency in rural areas of several developing countries. *Ex ante* cost-effectiveness studies suggest that biofortification is likely to be a cost-effective public health intervention (Stein et al. 2007, 2008; Meenakshi et al. 2010; de Steur et al. 2012). Efficacy studies conducted in highly controlled experimental settings have shown positive results for iron-rich beans, iron-rich rice, and provitamin A-rich orange sweet potato (OSP) (e.g., Haas et al. 2005; van Jaarsveld et al. 2005; Luna et al. 2012). Most recently, an effectiveness study was conducted in Uganda and Mozambique to evaluate the impact of an intervention that delivered OSP planting material in rural areas. This study showed that the intervention resulted in high rates of adoption and consumption of OSP, leading to increased vitamin A intakes and hence reduced vitamin A deficiency among children with low levels of vitamin A in the blood at the start of the study (Hotz et al. 2012a; Hotz et al. 2012b). This intervention was found to cost US$15–US$20 per Disability Adjusted Life Years (DALY)[1] saved, which by World Bank standards is considered highly cost-effective (World Bank 1993; HarvestPlus 2010). Following these favorable results, interventions for delivery of provitamin A-rich OSP are being scaled up in Uganda and Mozambique and are being planned or implemented in other African countries.

Additional efficacy and effectiveness studies are being implemented or are in planning stages. As evidence in favor of biofortification builds, various stakeholders are increasingly interested in investing in this intervention as a cost-effective means for reducing hidden hunger. These stakeholders include donor agencies and international and national non-governmental and government organizations from both the agricultural and health sectors, as well as private seed and food companies. All of these stakeholders need evidence-based information on where to target specific biofortified crops to achieve highest nutrition, and hence health, impacts most cost-effectively.

The main aim of this paper is to contribute to filling this information gap by generating country-crop-micronutrient specific biofortification prioritization indices (BPIs) that will rank countries both globally and within regions (Africa, Asia, and LAC) according to their suitability for investment in biofortification interventions. With biofortification interventions, the largest impact in terms of reduction of DALYs could potentially be achieved

1 The disability-adjusted life year (DALY) is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability, or early death. Health interventions are evaluated according to the total number of DALYs they can save in the affected/vulnerable population and the cost per DALY saved. For application of the DALY concept to calculate the cost-effectiveness of biofortification, see Stein et al. (2005).

for those country-crop-micronutrient combinations that exhibit (i) high per-capita consumption of the specific crop sourced by domestic production; (ii) high intensity of production of the specific crop in terms of share of harvested area and of land-labor-ratio; and (iii) high micronutrient deficiency rates for the micronutrient that can be bred into the specific crop.

A BPI is calculated by using secondary, country-level data compiled from various sources including the Food and Agriculture Organization (FAO) of the United Nations, the World Health Organization (WHO), and the United States Department of Agriculture (USDA). Similar to the Human Development Index (HDI) (UNDP 1990) and Global Hunger Index (GHI) (IFPRI/Welthungerhilfe 2006), we use a heuristic approach to generate the BPI. While the GHI uses arithmetic mean to aggregate its three subindices, the revised version of the HDI uses geometric mean (UNDP 2013). Similar to the GHI and HDI, we generate three subindices to calculate BPI: one each for the production and consumption of the crop and one for the micronutrient deficiency. These subindices are then combined using geometric mean. This is preferred to arithmetic mean as the three indices are not substitutable. We also generate a "weighted" BPI that takes into account either the countries' (i) share of the target population (children age 6–59 months and women of childbearing age) in the global target population or (ii) the share of cultivated land area for a specific crop in the global cultivated land area for that crop. For stakeholders whose mandate is large-scale health impact, population-weighted BPI would be most appropriate. Whereas for stakeholders interested in seed multiplication and marketing aspects, area-weighted BPI could be more useful. Both weights implicitly consider cost aspects, since fixed investments in biofortification for a given country can either benefit more people or be planted on more land.

The results reveal that for the 127 countries included in the analysis, African countries rank highest for vitamin A-rich crops, including maize, cassava, and sweet potato, and Asian countries rank highest for zinc-rich cereals, including wheat and rice. For rice, Africa also offers some suitable countries that could generate high levels of impact. For iron biofortified beans, several countries in Africa and some in LAC surface as high return-on-investment potentials. Finally, for iron biofortified pearl millet, both Africa (especially West Africa) and South Asia constitute suitable candidate sites for investment. Several of the findings are in line with currently implemented and planned biofortification interventions, while others suggest new avenues for exploration.

The main limitations of the BPI are three-fold. First, since biofortification is a relatively new intervention, there is very little available data on the costs of this intervention. Therefore, the BPI does not explicitly measure the cost-effectiveness of biofortification in reducing the DALY burden of micronutrient deficiency. However, several of the variables used for the construction of the BPI should be included when calculating the costs of biofortification interventions. Second, data are at a national level, i.e., at the highest level of aggregation for each country; therefore, the BPI may overlook important within-country information. For example, a particular crop may be important in terms of production and consumption in one area of a country, whereas high rates of micronutrient deficiency may exist in another area. The national average may hide this, especially for countries with large differences in agroecological and climatic variation, as well as unequal distributions of income, which is highly associated with diet quality and hence with micronutrient deficiency levels. A third key limitation is the potential biases that may arise as a result of the aggregated consumption figures used for BPI calculations. It is likely that the national-level consumption figures are downward biased for rural households that are more likely to consume more staple crops than their urban counterparts. It is also possible that consumption figures are upward biased because the target populations (especially children age 6–59 months) consume less than the average person.

The rest of the paper unfolds as follows: the following section presents the conceptual framework and the methodology used to develop the BPI. Section 3 reports the data sources. Section 4 presents the top 15 country rankings, by region and crop, for unweighted and weighted BPI. Section 5 discusses the limitations of this study in great detail, and the final section concludes the paper with implications for investment in biofortification and future research avenues.

2. CONCEPTUAL FRAMEWORK AND METHODOLOGY

2.1 Concept

The BPI is a composite, crop-specific index accounting for the intensity and level of production and consumption of a specific crop in any given country and the deficiency levels for the micronutrient(s) with which the specific crop can be enriched. According to the BPI for each crop, countries with higher indices should be considered for prioritization for biofortification interventions.

Three basic conditions need to be fulfilled for a country to be considered a suitable candidate for introduction of a biofortified crop:

1) The country must be a producer of the crop, and at least part of the output must be retained for domestic consumption, i.e., not all of the output should be exported.

2) The country's population must consume a substantial quantity of the crop under consideration from their own domestic production.

3) The country's population suffers from deficiencies for the key micronutrients, namely vitamin A, zinc, or iron.

The first condition suggests that, *ceteris paribus*, the larger the production in terms of area or volume of output harvested and the lower the share of production being exported, the more opportunity the country offers in terms of using biofortified varieties of that crop to reduce hidden hunger in the country. The second condition suggests that the higher the quantity consumed per capita, the more likely it is for biofortification to make a sizeable difference in the micronutrient intake of a country's population. Some countries may, however, have large per-capita consumption levels, but most, or all, of the food may be imported. This would mean such a country would not meet production condition one. Last but not least, condition three suggests that, *ceteris paribus*, the higher a country's population's micronutrient deficiency level, the higher the impact of biofortification would be, provided that conditions one and two are met.

In addition to consumption, production, and micronutrient deficiency, there are other factors that may be considered for inclusion in such an index. These factors include income, hunger, or poverty level of a country; proportion of the population affected by infectious diseases; and quality of water and sanitation. One may also consider certain macro-level and political dimensions, such as the quality of governance and its status as a recipient for (fortified) food aid and the availability and coverage of other micronutrient interventions in the country, such as supplementation and fortification. All of these dimensions may contribute to exacerbating or reducing DALYs lost due to micronutrient deficiency.

Inclusion of additional dimensions, however, comes at the risk of diluting an index and losing focus. Furthermore, each additional dimension needs to be supported by sufficient cross-country data of comparable quality and from similar time periods. For example, the Demographic and Health Surveys (DHS) contain a number of variables on infectious diseases, water quality, and sanitation that one might consider including in the BPI. Inclusion of these variables, however, implies that several countries for which DHS survey data do not exist would have to be dropped from the sample. Even for those countries that would remain in the database, the vast differences in reference periods may not allow for effective cross-country comparison. These concerns led to the design of an index that focuses solely on the three above-mentioned dimensions.

2.2 Description of the Method

2.2.1 Definition of the Sub-indices

Calculation of the BPI is based on three underlying indices that seek to capture the three above-mentioned dimensions and the related conditions.

1) The consumption index measures the intensity of consumption of the specific crop, adjusted for the share of the crop's total national consumption that is imported. The index is computed from two variables:

i. Consumption per capita per year, and

ii. Import dependency ratio (IDR) or Import share.[2]

The higher the per-capita consumption of a crop, the easier it is to improve target populations' micronutrient intake through biofortification of that crop. As countries differ in their national self-sufficiency for particular crops, we also take into account the dependency of the country on imports of that crop. Holding per-capita consumption constant, countries with high import dependency should

2 Provided that the production of a country is positive, the import share is calculated as IDR = Imports / (Production + Imports - Exports). The import share is 1 if the production is 0 and the per-capita consumption of a country is positive. The export share used in the calculation of the production index is calculated as the volume of exports of a specific crop divided by the sum of production and imports of the crop. There are a number of countries that produce little or nothing of a specific crop, but import sizeable quantities for national consumption and—in some cases—also re-export to other countries.

receive less priority compared to countries that produce themselves most, if not all, of the domestic consumption of the crop in question.

2) The production index measures the intensity of production of each crop in a country. Variables included are:

i. Area harvested of a specific crop, measured as a percentage of total area harvested in the country

ii. Per-capita area harvested, and

iii. Export share.

The first two variables measure the relative importance of a particular crop in the agricultural sector of a country. For the crop development and delivery costs associated with the introduction of biofortified crops, the higher the total land area allocated to a particular crop and the higher the share of agricultural land allocated to that crop, the lower the per hectare unit costs of seed multiplication and delivery would be. The amount of seed used in a country is mainly driven by the size of cultivated area, not by the amount of (desired or achieved) production. With a large land area devoted to a particular crop, economies of scale can be realized for the investments that will be made in breeding, seed multiplication, delivery, marketing, and information diffusion. While the unweighted version of the production index only measures the intensity of a crop within a given country, the area-weighted version also takes the size of the land area into consideration, relative to the global cultivated cropping area.

The per-capita area harvested variable measures the factor intensity, i.e., the intensity of land allocated to a particular crop in relation to labor, proxied by total population. A food crop that features a large land-to-labor ratio is likely to be more important for the overall food supply of a country and will, therefore, be credited greater political importance with respect to food security. A food crop with a large share in total cultivated area will also receive greater political importance by other stakeholders such as seed companies.

Ceteris paribus, higher values for the area share and land-labor ratio variables result in a higher BPI. Some countries, however, export a large share of their crop production. In order to take these exports into account, the two variables outlined above are corrected by the export share in national production.

3) The micronutrient deficiency index measures the extent of micronutrient deficiency in the country. Each one of the seven staple crops that are targeted for biofortification contain higher amounts of one of three micronutrients, vitamin A, iron, or zinc, recognized by the WHO as the most limiting in diets. Maize, cassava, and sweet potato are biofortified with provitamin A; beans and pearl millet are biofortified with iron; and rice and wheat are biofortified with zinc. It was found that biofortification of cereals with zinc also results in increased iron content (Johnson et al. 2011). Three separate indices are developed for each micronutrient.

1. Vitamin A micronutrient deficiency index includes:

i. Proportion of preschool-age children with retinol < 0.70 µmol/l, and

ii. Age-standardized DALYs lost per 100,000 inhabitants to vitamin A deficiency (VAD).

2. Iron micronutrient deficiency index includes:

i. Proportion of preschool-age children with hemoglobin (Hb) < 110 g/l, and

ii. Age-standardized DALYs lost per 100,000 inhabitants to iron deficiency anemia (IDA).

3. Zinc micronutrient deficiency index includes:

i. Percentage of population at risk of inadequate intake of zinc, and

ii. Prevalence of stunting among children 6–59 months of age.

For each micronutrient index, the two variables used are correlated with each other. For instance, low Hb prevalence is used as is, but it is also included in the calculation of DALYs lost from IDA. However, in spite of their correlation, these two variables still provide different pieces of information, and we prefer to calculate these subindices based on two rather than one variable. Using two variables as opposed to only one also allows us to partially mitigate the lack of reliability and precision of some of the single variables.

2.2.2 Calculation of the Sub-Indices

Variables used for the construction of the three sub-indices all feature different units of measurement. For mathematical addition and aggregation of variables into subindices, they should be converted into new variables without measurement units (e.g., kilogram or hectare). We use the conversion method used by the HDI to scale the variables. All variables are rescaled to a range between 0 and 1 by applying the following formula:

$$Rescaled\ value = \frac{actual\ value - minimum\ value}{maximum\ value - minimum\ value} \quad (1)$$

The minimum and maximum values for each indicator were either the minimum and maximum values among the observations for all countries in the dataset, or zero and 100, for variables expressing percentage values, such as the import or export shares. These goalpost values are listed in Table 1 below. The value range for all of the rescaled variables is between zero and 1, and all variables are free of unit of measurement.

Similar to the HDI and GHI, we employ a heuristic approach that uses an arbitrary set of weights for weighing individual indicators for the computation of these subindices. In the following equations, the superscript *r* indicates that the variable is rescaled by using equation 1.

$$\textit{Consumption Index} = \textit{Consumption per capita per year}^{r}\,(1 - \textit{import share}^{r}) \quad (2)$$

The main indicator of the consumption index is consumption per capita. As explained above, for the construction of the consumption index, we account for the proportion of national consumption that is supplied by imports by multiplying it with the term (1 – *import share*). If the quantity consumed in a given country is entirely imported and, therefore, national production of the crop is 0, the import share equals 1.

$$\textit{Production Index} = (1/2 * \textit{P.c. area harvested}^{r} + 1/2 * \textit{Ag. land allocated to the crop}^{r}) * (1 - \textit{export share}^{r}) \quad (3)$$

As explained above, the production index is comprised of three indicators: per-capita area harvested to a specific crop, share of area harvested to this crop in total area harvested in a country, and export share. There are a

Table 1: Minimum and Maximum Values Used for Rescaling the Variables

Index	Variable (Unit)	Crop	Min	Max (Country)
Consumption Index	*Consumption per capita per year (kg/year)*	Beans	0	29.3 (Rwanda)
		Maize		149.3 (Lesotho)
		Sweet potato		88.9 (Burundi)
		Cassava		261.4 (Congo)
		Rice		259.9 (Bangladesh)
		Wheat		207.5 (Azerbaijan)
	Import or export shares (%)	All crops	0	100
Production Index	*Per-capita area harvested (m^2)*	Beans	0	567.1 (Myanmar)
		Maize		1230.1 (Paraguay)
		Sweet potato		254.3 (Equatorial Guinea)
		Cassava		548.5 (Angola)
		Rice		1963.9 (Cambodia)
		Wheat		8197.9 (Kazakhstan)
	Amount of land allocated to the specific crop as percentage of total area harvested in the country (%)	All crops	0	100
Micronutrient Deficiency Index (Vitamin A)	*Proportion of preschool-age children with retinol < 0.70 umol/l (%)*		0	100
	Age-standardized DALYs lost per 100,000 inhabitants to VAD		0	402.0 (Liberia)
Micronutrient Deficiency Index (Iron)	*Proportion of preschool-age children with Hb < 110 g/l (%)*		0	100
	Age-standardized DALYs lost per 100,000 inhabitants to IDA		0	1206.0 (Haiti)
Micronutrient Deficiency Index (Zinc)	*Proportion of population at risk of inadequate intake of zinc (%)*		0	100
	Prevalence of stunting among children 6–59 months of age (%)		0	100

number of countries that export a large share of their production. In order to measure the share of production that is consumed domestically, the sum of these two variables is multiplied by the factor (1 – *export share*). For countries not producing a particular crop, both the area share and the amount of land allocated to the crop is zero. Therefore, the production index becomes zero.

The following formulae were used to calculate the three micronutrient indices:

$$\textit{Micronutrient Index (Vitamin A)} = 1/2 * \textit{Serum Retinol } 0.7^r + 1/2 * \textit{DALYs by VAD}^r \quad (4)$$

$$\textit{Micronutrient Index (Iron)} = 1/2 * \textit{Hb less } 110^r + 1/2 * \textit{DALYs by IDA}^r \quad (5)$$

$$\textit{Micronutrient Index (Zinc)} = 1/2 * \textit{Inadequate Zinc}^r + 1/2 * \textit{Stunting prevalence}^r \quad (6)$$

Similar to the most recent HDI (UNDP, 2013), we use geometric mean, rather than the arithmetic mean employed by GHI. The main reason for our use of geometric mean is that the presence of all of the three indices are necessary for biofortification interventions to have a measurable impact. In other words, these subindices should complement, rather than substitute for, one another. Due to the high and significant correlation between production and consumption subindices, a geometric mean of these two is calculated prior to calculating the overall geometric mean. This ensures that an equal weight is given to the micronutrient index and to the geometric mean (i.e., the square root) of the production and the consumption index. The final BPI is calculated as:

$$\textit{Biofortification Priority Index (BPI)} = \sqrt{(\sqrt{\textit{Production Index} * \textit{Consumption Index}}) * \textit{Micronutrient Deficiency Index}} \quad (7)$$

Therefore, equation 7 yields a BPI between 0 and 1. For ease of exposition, we multiply equation 7 by 100 and present a BPI from 0 to 100. We then use equation 1 to rescale the crop-specific BPI value in the range of 0 to 100. BPI results for each crop are presented by region in section 4.

2.3 The Size of a Country Matters but…

The proposed production index deliberately avoids including variables that measure the country's size of production in absolute terms, such as the quantity produced or area harvested. Likewise, the consumption index deliberately avoids including the size of the population or the total amount consumed in a country. The inclusion of size-specific variables in production or consumption would unnecessarily bias the BPI toward larger countries, such as India, China and Brazil, at the expense of smaller ones. The unweighted BPI seeks to measure a country's potential for biofortification, irrespective of its size or population.

For a number of reasons, large countries may offer, *ceteris paribus*, better opportunities for biofortification compared to smaller ones. First, larger areas may be harvested for a particular crop, generating economies-of-scale dilution of fixed costs, such as those spent on breeding, marketing, and delivery. Large countries, however, often feature more diverse agroecological and agroclimatic conditions; suitable varieties, therefore, should be bred and developed for these. In addition, one may face institutional and socioeconomic diversity, such as differences in farmers' adoption behavior or in consumer preferences, that would warrant a host of marketing and delivery strategies for different areas in larger (and likely more diverse) countries. Hence, the economies-of-scale argument regarding cost dilution in larger countries also has its limitations.

The second reason larger countries may offer a better opportunity is their larger target population sizes. The size of the target population, combined with the extent of the micronutrient deficiency problem in the country, has a direct influence on the DALYs that can potentially be saved through biofortified crops. Hence, larger countries offer more opportunities in terms of absolute number of DALYs saved, simply because of their larger population sizes.

In a nutshell, all other factors held constant, larger countries could have more favorable cost-benefit-ratios. But the definition of a "large" country can differ by stakeholder. Some may perceive size in terms of area and/or volume of production for a particular crop, while others focus on the number of children and women who could be reached with biofortified foods. Still others may focus on the number of DALYs saved through the intervention.

We account for these differences by calculating two alternative indices that take land area and size of the target population into consideration. In general, if A is a weight measuring the size of a country in relation to all countries, and A is a variable scaled between 0 and 1, then the BPI of any country can be weighted by the variable A as follows:

$$\textit{BPI weighted} = \textit{BPI}^r * A * 100 \quad (8)$$

The first weighted index uses a country's share of harvested area for a specific crop in the global area harvested to that crop as a weight. The second weight uses a country's target population (i.e., the sum of the number of children age 6–59 months and the number of women of childbearing age) divided by the global target population. Here "global" refers to the 127 countries in our database. The resulting figures from equation (8) may range from zero to any positive number. For comparison purposes, the re-scaling method shown in equation 1 is used here, and the resulting figures, which range from zero to 1, are then rescaled with the factor 100 so as to obtain a value from zero to 100. These weighted BPIs for each crop can be directly compared to the unweighted BPI for the same crop.

Some of the stakeholders interested in investing in biofortification, such as international NGOs or multilateral donor agencies, often have a global lens. The primary objective of such stakeholders would most likely be the optimization of the size of the population reached with biofortification, given a fixed budget. Under such circumstances, these stakeholders could benefit from population-weighted BPIs, which take into consideration the share (percentage) of each country's target population (i.e., women of childbearing age and children age 6–59 months) in the global target population. Alternatively, other stakeholders may have maximization of production as their principle concern. A seed company could, for example, need a minimum land area allocated to a crop to reach a satisfactory return on its investment. For such stakeholders, area allocated to the staple crops would be the driving factor in their choice of investment opportunities, and they would, therefore, benefit from the use of area-weighted BPIs, which take into consideration the share of each country's land area allocated to a specific crop in global land area allocated to that crop.

3. DATA

Table 2 provides a summary of the variables used to calculate the three subindices, as well as the data sources and years. The main source of production, consumption, import, and export data is FAOSTAT. For data on the six indicators of micronutrient deficiency, data from WHO, DHS, and the International Zinc Nutrition Consultative Group (IZiNCG) are used. Data on the number of women of childbearing age (15–49 years) and children 0–59 months are obtained from the World Bank.

The data used to generate the three subindices are gathered for a total of 127 countries: 51 countries from Africa, 44 from Asia, and 32 from LAC. Japan, South Korea, and Israel, all high-income Organisation for Economic Co-operation and Development (OECD) member countries, were excluded from this list. Other

Table 2: Variables Used for the Calculation of the Unweighted and Weighted BPIs

Underlying Index	Variable Name	Variable Explanation	Main Data Source and Year
Production Index	Share of area harvested (%)	Total area harvested of a specific crop (ha)/total agricultural land of a country (ha)	FAO 2010
	Per-capita area harvested (ha)	Total area harvested of a specific crop (ha)/total population in the country	FAO 2010
	Export share (%)	If Production greater than 0: Export share =Exports/(Production+Imports); otherwise export share is 0 %	FAO 2010
Consumption Index	Per-capita food consumption	Per-capita food consumption (kg/year)	FAO 2010
	Import Dependency Ratio=Import Share (%)	If Production greater than 0: Import share =Imports/(Production+Imports-Exports); otherwise, import share is 10 %	FAO 2010
Micronutrient Deficiency Index	**For vitamin A**		
	SerumRetinol07	Proportion of preschool-age children with retinol < 0.70 umol/l	WHO 2009
	DALYs VAD	Age-standardized DALYs lost per 100,000 inhabitants to VAD	WHO 2002
	For zinc		
	InadequateZinc	Percentage of population at risk of inadequate intake of zinc	Hotz and Brown 2004
	Stunting	Prevalence of stunting among children age 6-59 months	WHO 2008
	For iron		
	DALYs IDA	Age-standardized DALYs lost per 100,000 inhabitants to IDA	WHO 2002
	HbLess110	Proportion of preschool-age children with Hb < 110 g/l	ICF International 2012 WHO 2008
Population weight	Share of rural target population	Rural target population (women childbearing age and children 0-59 months) in country/Rural target population "globally"	World Bank 2012
Land area share weight	Share of crop area	Total area harvested of a specific crop in a given country (ha)/total area harvested of specific crop "globally" (ha)	FAO 2010

OECD member countries, namely Mexico, Chile, and Turkey were included in this study as they are not categorized as high-income countries according to the World Bank. Western Sahara and the Bahamas were also excluded because of missing data for most of the variables. A full list of the 127 countries can be found in Appendix 1.

FAOSTAT's database on the major grains, i.e., rice, wheat, and maize, is complete for most of the variables used in the analysis. However, the data situation is by far weaker for sweet potatoes and cassava. For beans, FAOSTAT only reports data for the "dry beans" category, which includes a variety of beans that are not targeted for biofortification. Similarly, FAOSTAT reports all types of millet under the "millet" category. In both cases, consulted experts (Wolfgang Pfeiffer and Steve Beebe, personal communication, 2013) confirmed that common bean types targeted for biofortification comprise the majority of the "dry beans" data for most countries (with the exception of India and Myanmar), and the pearl millet targeted for biofortification comprises the majority of the "millet" data.

Additional data sources and information are used to reduce the number of missing values on production, consumption, export, and import data for the study crops. These major sources include the United States Department of Agriculture-Foreign Agricultural Service (USDA FAS), the International Rice Research Institute (IRRI), the CIA World Factbook, and Index Mundi (2006), as well as Google and Google scholar searches. For those few countries for which no production, consumption, export, or import data could be found for a certain crop, consumption and/or production of that crop was assumed to be zero.

Missing data for the micronutrient deficiency indicators were replaced with the mean value of the respective income tercile of the sub-region, if the region included at least nine countries with valid data (World Bank 2011). The income variable used to determine terciles per region was the gross national income (GNI) per capita in purchasing power parity, as of 2010. If a region had less than nine valid observations for a particular variable, only two income groups were created for which the respective averages were calculated to replace missing data.

In cases where data on both a malnutrition variable and the GNI per capita were missing, the mean value of the whole region was taken as a proxy. Moreover, all countries in the Caribbean (except Haiti) and a number of Central and South American countries had missing values for DALYs lost to VAD. Therefore, it was not possible to use a GNI-specific group mean, and the mean value for all LAC countries with observed values for DALYs lost to VAD was used to replace missing values for the remaining countries in that continent. For the zinc deficiency index, the same tercile approach was used to replace missing values for the variable measuring the prevalence of stunting. However, instead of classifying countries by income terciles, countries were classified regionally based on inadequate zinc intake terciles. Detailed documentation on missing data and data sources, methods, and assumptions used to fill these can be obtained from the authors upon request.

4. RESULTS

This section presents the unweighted BPIs for the top 15 countries, by crop and region, as well as population and area weighted BPIs for the three regions combined. Unweighted and weighted BPIs for each crop are visualized on regional maps. Maps for the unweighted BPIs are presented below, and those for the weighted BPIs can be found in Appendix 2. BPIs for all 127 countries studied, as well as the subindices and the data used to calculate these, can be obtained from the authors upon request.

4.1 Unweighted BPI, by Crop and Region

Cassava

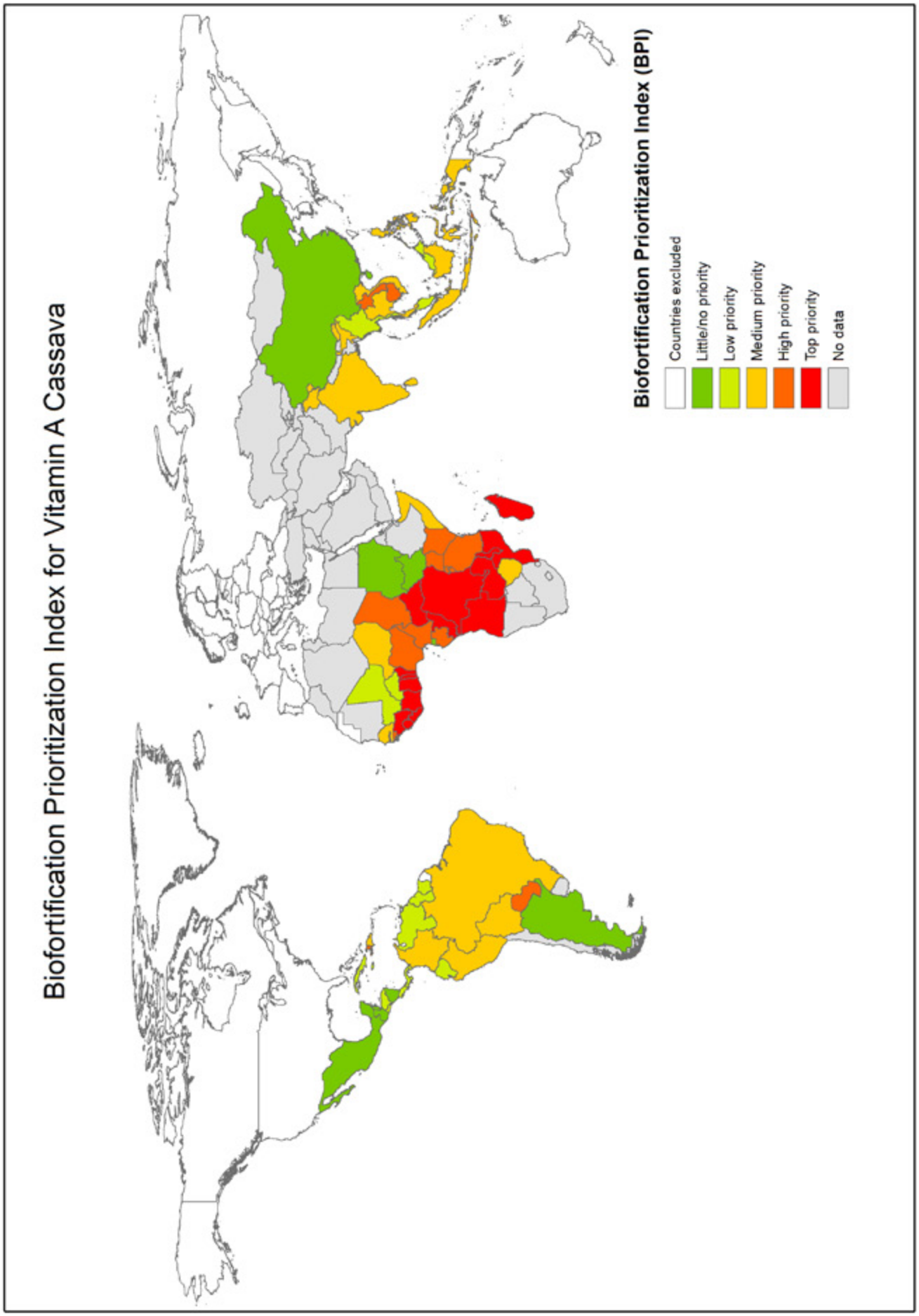
Table 3 presents the top 15 countries that could be considered for cassava biofortification interventions in each of the three regions studied. Overall, the BPIs reveal that the top 15 countries for cassava are in Africa; therefore, investments in provitamin A-rich cassava could generate the biggest impact on this continent.

Currently the Democratic Republic of Congo (DRC) and Nigeria are targeted for the introduction of yellow cassava varieties. Nigeria, however, does not make it to top 15 for the unweighted BPI reported in Table 3. Nigeria is a large country with significant heterogeneity in agroecological conditions and related consumption and production patterns. Cassava production is concentrated in the southern states of the country, and a subnational BPI, calculated for each one of the Nigerian states, could yield higher BPI values than some of the countries reported in Table 3. At a national level, however, this table shows that there are many African countries other than Nigeria where the intensity of cassava production and consumption, as well as the prevalence of vitamin A deficiency, is higher.

Table 3: BPI Rankings for Top 15 Countries: Cassava in Africa, Asia, and LAC

Regional Rank	Africa		Asia		LAC	
1	Mozambique	100.0	Timor-Leste	33.5	Paraguay	31.9
2	Angola	97.9	Cambodia	23.3	Haiti	30.9
3	Ghana	93.1	Laos	20.1	Brazil	17.9
4	Liberia	92.2	Philippines	20.0	Peru	13.8
5	Benin	90.4	Indonesia	19.7	Bolivia	13.5
6	Central African Republic	89.0	Thailand	17.1	Dominican Republic	10.6
7	DR Congo	81.4	Sri Lanka	12.7	Colombia	10.0
8	Sierra Leone	76.9	Viet Nam	10.8	Saint Lucia	9.0
9	Côte d'Ivoire	61.2	India	10.4	Costa Rica	7.6
10	Zambia	58.4	Myanmar	9.7	Venezuela	7.1
11	Malawi	58.4	Malaysia	4.8	Cuba	6.7
12	Congo	55.3	China	2.7	Ecuador	6.1
13	Togo	51.8			Jamaica	5.7
14	Madagascar	51.5			Suriname	5.6
15	Guinea	51.3			Guyana	4.6

Figure 1: BPI Map for Cassava



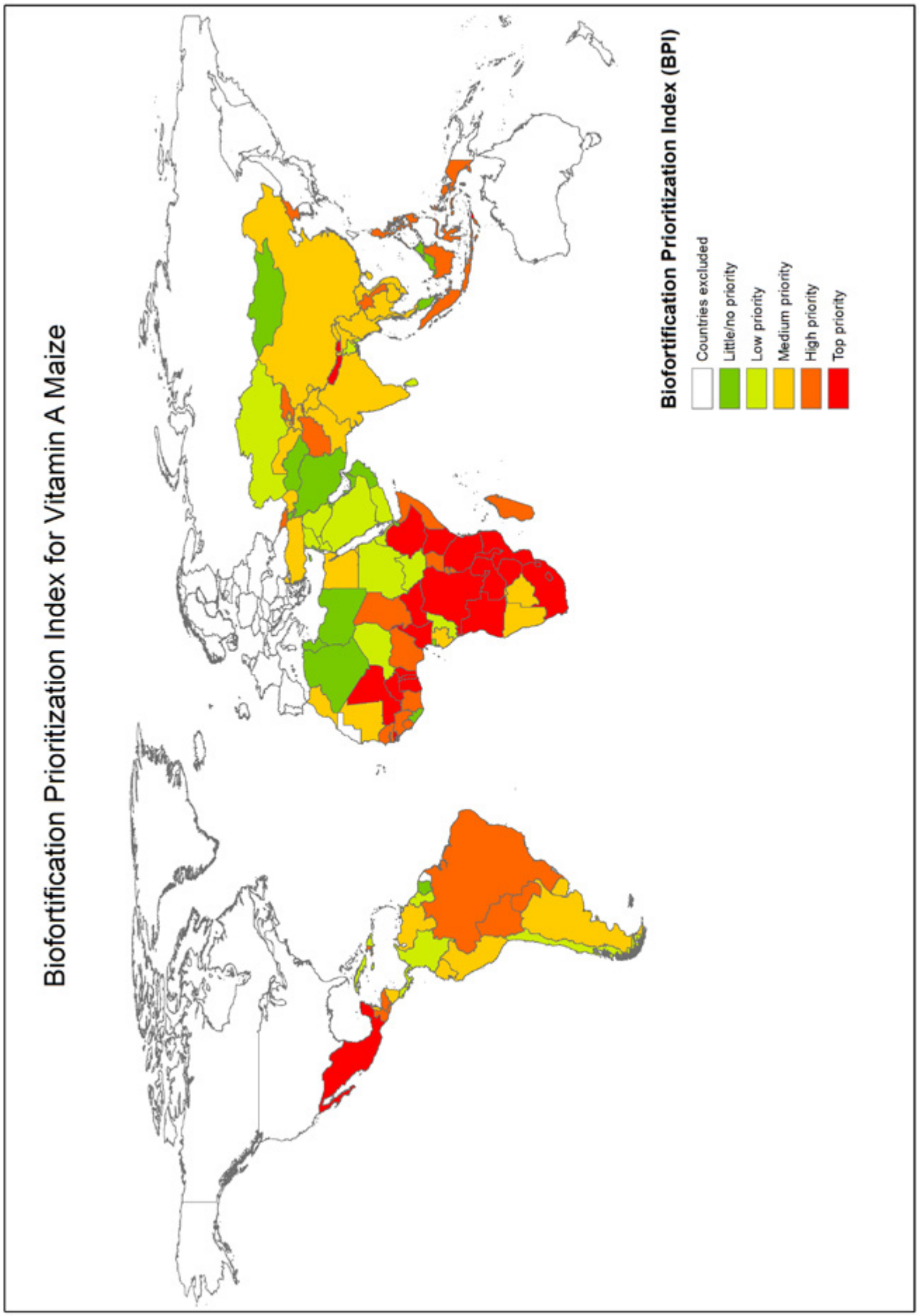
Maize

Table 4 presents the top 15 countries that could be considered for maize biofortification interventions in each of the three regions studied. Overall, the BPIs reveal that 14 of the top 15 countries for maize are in Africa; therefore, as shown with cassava, investments in provitamin A-rich maize could generate the biggest impact on this continent. The importance of this crop in Africa can be summarized with "Maize is life" (Smale 1995), a popular saying in Malawi. In Asia, the only country that makes it into the global top 15 (or even top 20) is Timor-Leste, which is number 9 in global rankings. Even though Mexico is the origin of maize, it comes in the global top 20 rankings at number 17.

Table 4: BPI Rankings for Top 15 Countries: Maize in Africa, Asia, and LAC

Regional Rank	Africa		Asia		LAC	
1	Malawi	100.0	Timor-Leste	59.4	Mexico	41.7
2	Benin	79.0	Nepal	35.9	Guatemala	30.5
3	Zambia	78.3	Bhutan	33.6	Haiti	29.6
4	Kenya	69.0	North Korea	30.8	Paraguay	27.8
5	Mozambique	65.9	Laos	30.6	Honduras	26.2
6	Angola	62.0	Philippines	24.5	El Salvador	25.1
7	Burkina Faso	61.5	Georgia	23.6	Bolivia	25.0
8	Zimbabwe	59.7	Indonesia	22.1	Brazil	20.1
9	Mali	57.6	Kyrgyzstan	20.6	Belize	19.0
10	Togo	53.8	Afghanistan	20.4	Uruguay	15.9
11	Tanzania	48.0	Cambodia	20.0	Venezuela	15.5
12	Ghana	47.5	India	19.6	Peru	12.7
13	Gambia	45.9	Myanmar	13.4	Nicaragua	12.4
14	Lesotho	44.3	Azerbaijan	12.1	Argentina	12.3
15	Swaziland	43.7	Viet Nam	12.0	Ecuador	11.4

Figure 2: BPI Map for Maize



Sweet Potato

Table 5 presents the top 15 countries that could be considered for sweet potato biofortification interventions in each of the three regions studied. Overall, the BPIs reveal that 12 of the top 15 countries for sweet potato are in Africa; therefore, as shown with cassava and maize, investments in provitamin A-rich OSP could generate the biggest impact on this continent.

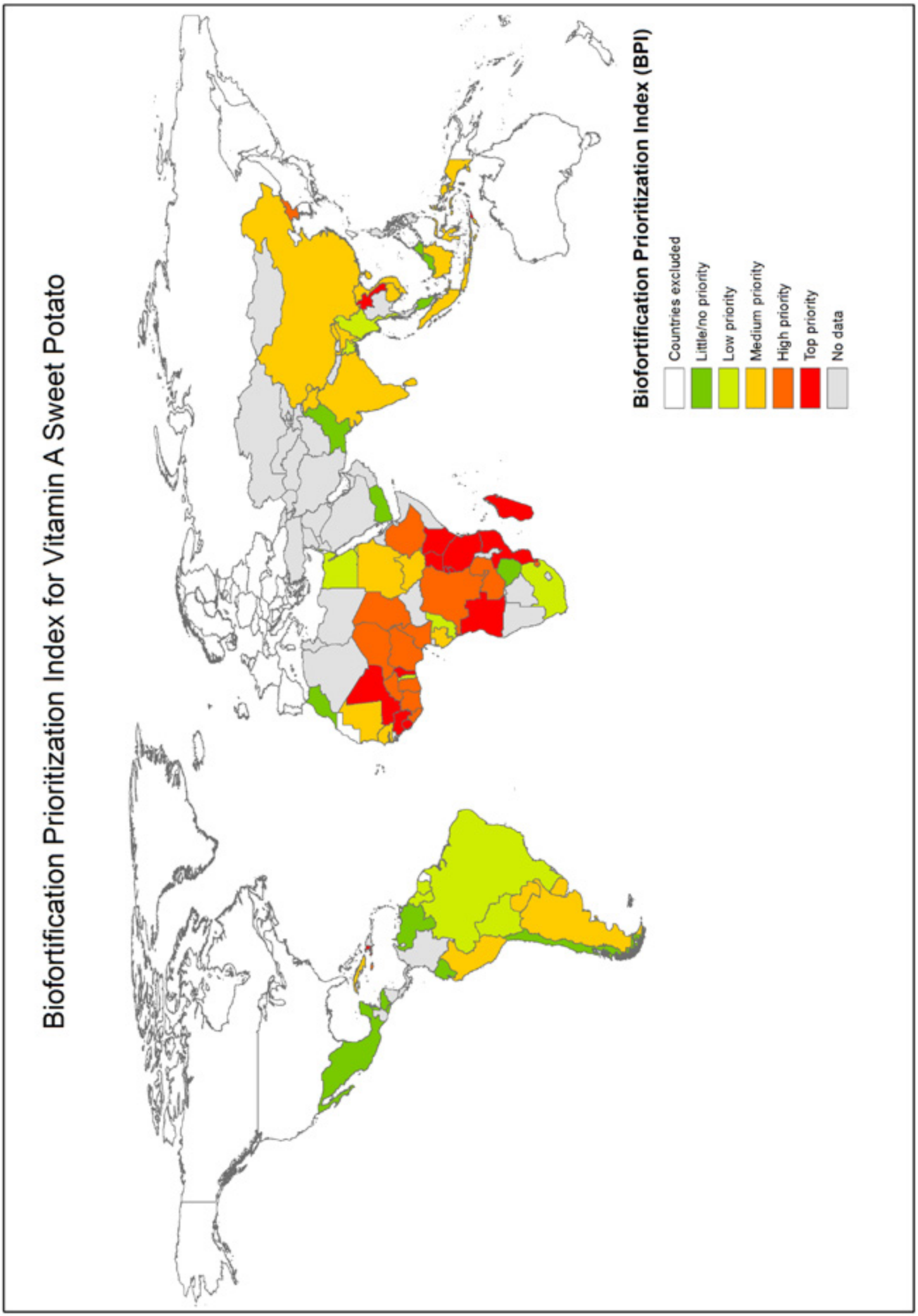
Since 2006, planting material for OSP is being delivered in Uganda and Mozambique. As reported in the introduction section, this intervention has resulted in significant and positive outcomes with regards to adoption, increase in vitamin A intakes, and reduction of vitamin A deficiency. OSP is also being introduced in several other African countries, including Angola, Kenya, Tanzania, Rwanda, Zambia, Ghana, and Nigeria, where interventions are already underway to adapt, multiply, and deliver OSP varieties.

Outside Africa, OSP could be considered as a promising strategy for combatting vitamin A deficiency in Haiti, Laos, and Timor-Leste.

Table 5: BPI Rankings for Top 15 Countries: Sweet Potato in Africa, Asia, and LAC

Regional Rank	Africa		Asia		LAC	
1	Angola	100.0	Laos	44.9	Haiti	49.4
2	Burundi	95.1	Timor-Leste	43.7	Jamaica	22.1
3	Uganda	93.1	North Korea	26.1	Cuba	17.4
4	Mozambique	81.7	China	20.8	Argentina	13.1
5	Rwanda	77.5	Cambodia	16.3	Paraguay	12.9
6	Tanzania	65.1	Indonesia	16.1	Uruguay	12.8
7	Sierra Leone	58.0	Viet Nam	14.5	Peru	12.8
8	Madagascar	58.0	Sri Lanka	12.0	Antigua and Barbuda	8.7
9	Guinea	57.4	India	10.6	Saint Vincent and the Grenadines	7.3
10	Kenya	48.9	Bangladesh	9.6	Grenada	7.2
11	Mali	47.1	Myanmar	9.4	Saint Kitts and Nevis	7.2
12	Benin	44.2	Pakistan	1.5	Barbados	7.0
13	Nigeria	42.7	Malaysia	1.5	Brazil	6.1
14	Zambia	41.7			Bolivia	5.8
15	Ghana	41.5			Guyana	5.6

Figure 3: BPI Map for Sweet Potato



Beans

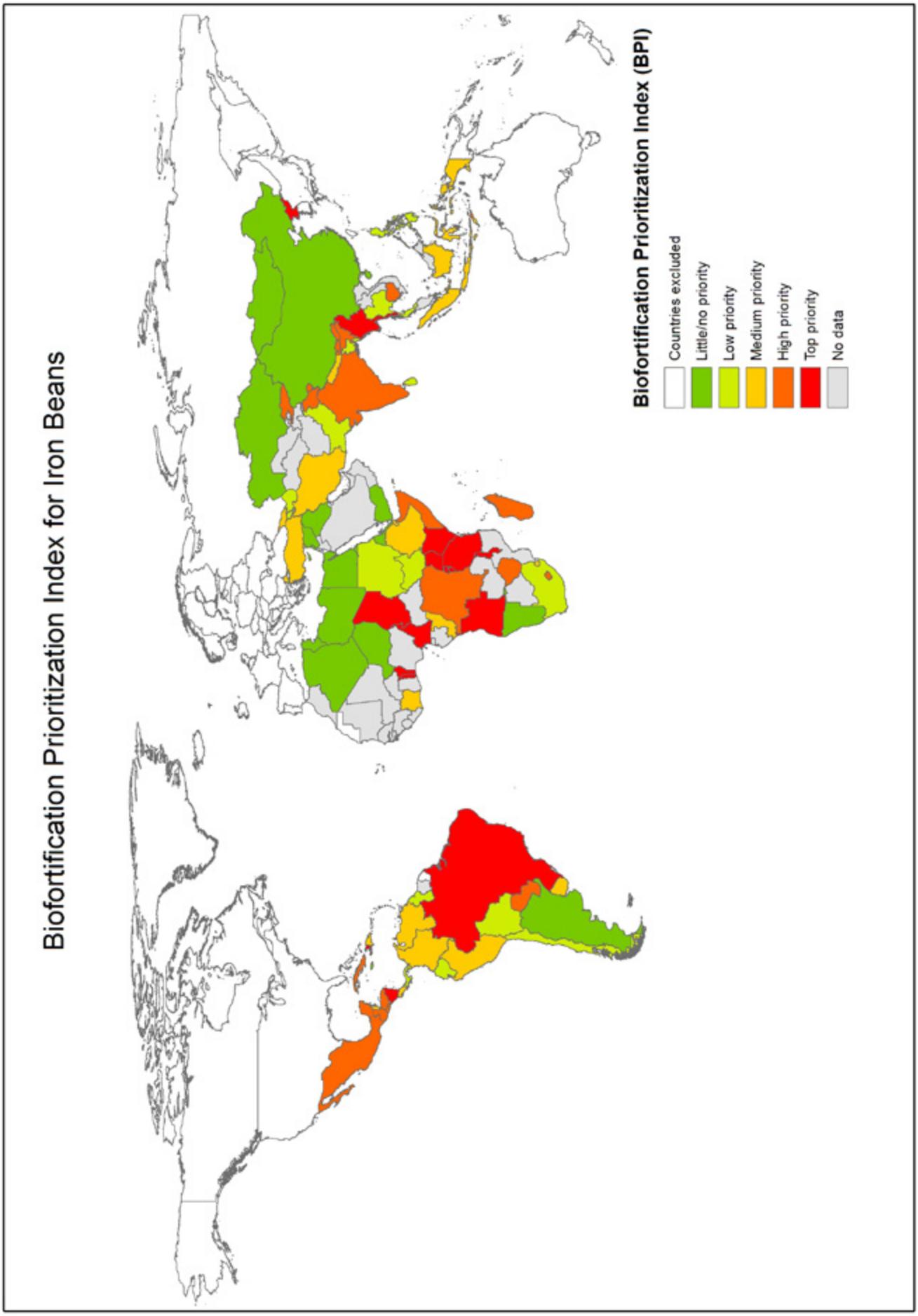
Table 6 presents the top 15 countries that could be considered for bean biofortification interventions in each of the three regions studied. Overall, the BPIs reveal that 10 of the top 15 countries for this crop are in Africa; therefore, as shown with cassava, maize, and sweet potato, investments in iron-rich beans could generate the biggest impact on this continent. In several of these countries, such as Rwanda, Uganda, and DRC, interventions are underway to multiply and deliver iron-rich bean varieties. In other countries (e.g., Burundi, Malawi, and Tanzania), adaptive breeding activities are taking place.

LAC is also a serious contender for iron-rich beans, with Haiti ranking in the top 10 globally; Brazil and Nicaragua ranking in the top 15, and Guatemala, Honduras and El Salvador ranking in the top 20. Among Asian countries, Myanmar (Burma) is the only one that makes it into the top 15, at number 5, in global rankings. However, it should be noted that, according to the experts, in the case of both Myanmar and India, the majority of beans measured under FAOSTAT's "dry bean" category are not the common beans (*phaseolus vulgaris*) that are being biofortified (Steve Beebe, personal communication, 2013).

Table 6: BPI Rankings for Top 15 Countries: Beans in Africa, Asia, and LAC

Regional Rank	Africa		Asia		LAC	
1	Rwanda	100.0	Myanmar	88.6	Haiti	82.8
2	Benin	98.9	North Korea	59.8	Brazil	70.7
3	Tanzania	94.9	India	49.9	Nicaragua	63.9
4	Burundi	92.0	Timor-Leste	45.6	Guatemala	59.3
5	Togo	84.7	Cambodia	41.9	El Salvador	47.2
6	Uganda	79.3	Bhutan	41.6	Honduras	47.1
7	Angola	78.5	Kyrgyzstan	34.4	Cuba	40.5
8	Kenya	77.2	Nepal	22.0	Mexico	40.5
9	Cameroon	70.1	Georgia	21.1	Paraguay	34.5
10	Chad	63.6	Iran	20.2	Belize	33.1
11	Malawi	61.3	Indonesia	19.5	Dominican Republic	24.9
12	Lesotho	45.0	Turkey	19.2	Peru	24.4
13	Zimbabwe	39.1	Armenia	17.9	Colombia	21.7
14	Somalia	38.7	Pakistan	17.5	Uruguay	20.6
15	Madagascar	35.4	Azerbaijan	16.5	Costa Rica	19.7

Figure 4: BPI Map for Beans



Pearl Millet

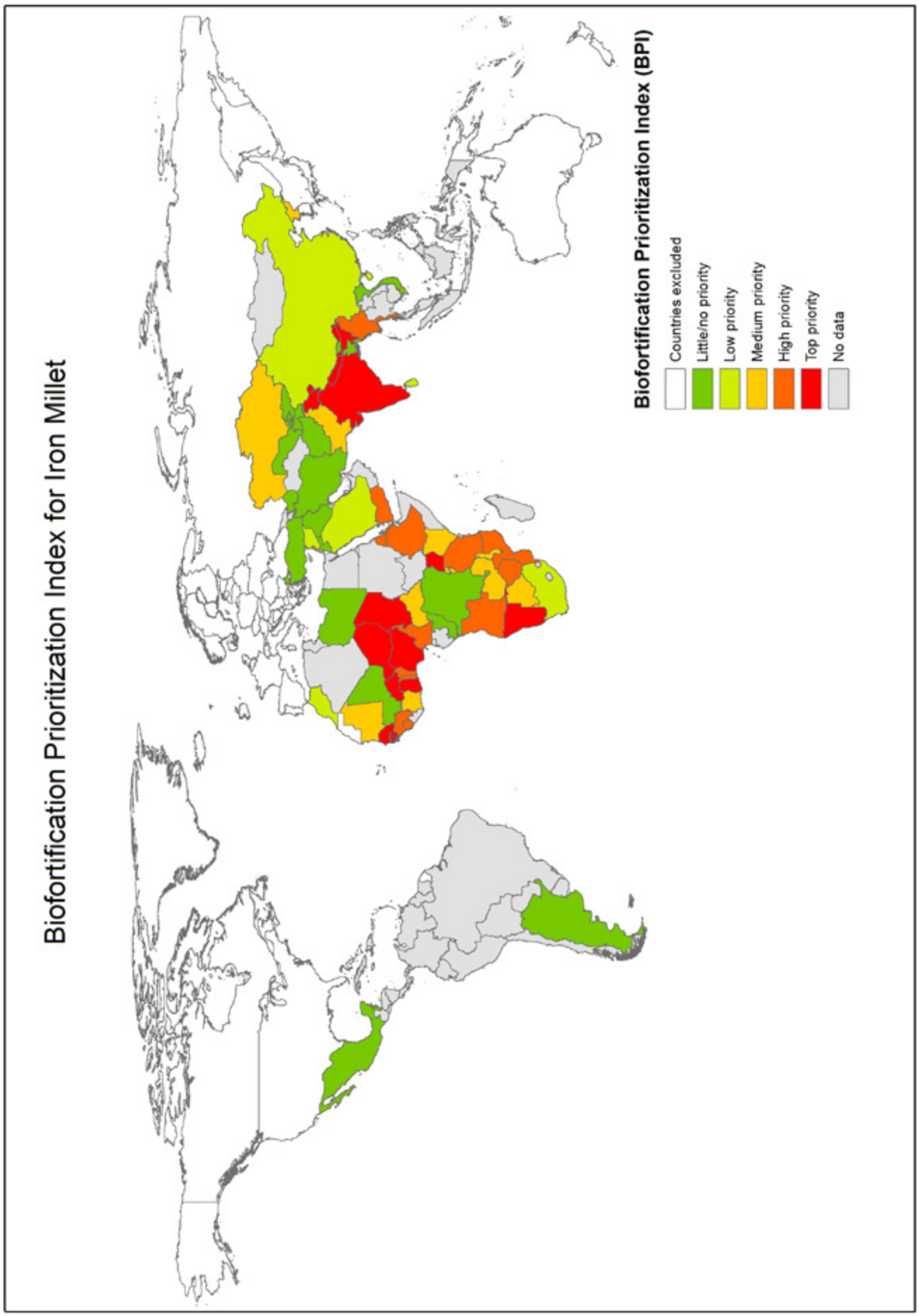
Table 7 presents the top 15 countries that could be considered for pearl millet biofortification interventions for Africa and Asia. LAC countries are not included in this table because their BPIs are zero as either this crop is not produced or not consumed in this region. Overall, the BPIs reveal that 12 of the top 15 countries for this crop are in Africa (especially in West Africa). Therefore, as shown with vitamin A biofortified crops and iron-rich beans, iron-rich pearl millet could generate the biggest impact on this continent.

In Asia, Nepal, India, and Myanmar are all promising candidates for investments in iron-rich pearl millet. In global rankings, Nepal is in the top 10 (number 10), and India is in the top 15 (number 11). It should be noted, however, that there is a significant variation in pearl millet consumption and production in India. Similar to the GHI calculated for Indian states (India State Hunger Index [ISHI], Menon, Deolalikar, and Bhaskar 2009), a BPI should be calculated for individual states. Interventions are underway to develop and deliver iron-rich pearl millet varieties in Maharashtra, one of the major pearl millet-producing and consuming states in India.

Table 7: BPI Rankings for Top 15 Countries: Pearl Millet in Africa and Asia

Regional Rank	Africa		Asia	
1	Niger	100.0	Nepal	23.5
2	Gambia	61.6	India	22.8
3	Burkina Faso	59.0	Myanmar	14.7
4	Chad	45.4	Yemen	12.2
5	Senegal	39.5	Pakistan	9.0
6	Nigeria	34.6	North Korea	5.8
7	Namibia	30.6	Kazakhstan	3.9
8	Guinea-Bissau	26.2	Sri Lanka	3.3
9	Uganda	23.7	China	2.4
10	Ghana	18.7	Saudi Arabia	1.8
11	Togo	17.2	Syria	1.4
12	Sierra Leone	16.3		
13	Guinea	14.6		
14	Zimbabwe	14.4		
15	Eritrea	14.1		

Figure 5: BPI Map for Pearl Millet



Rice

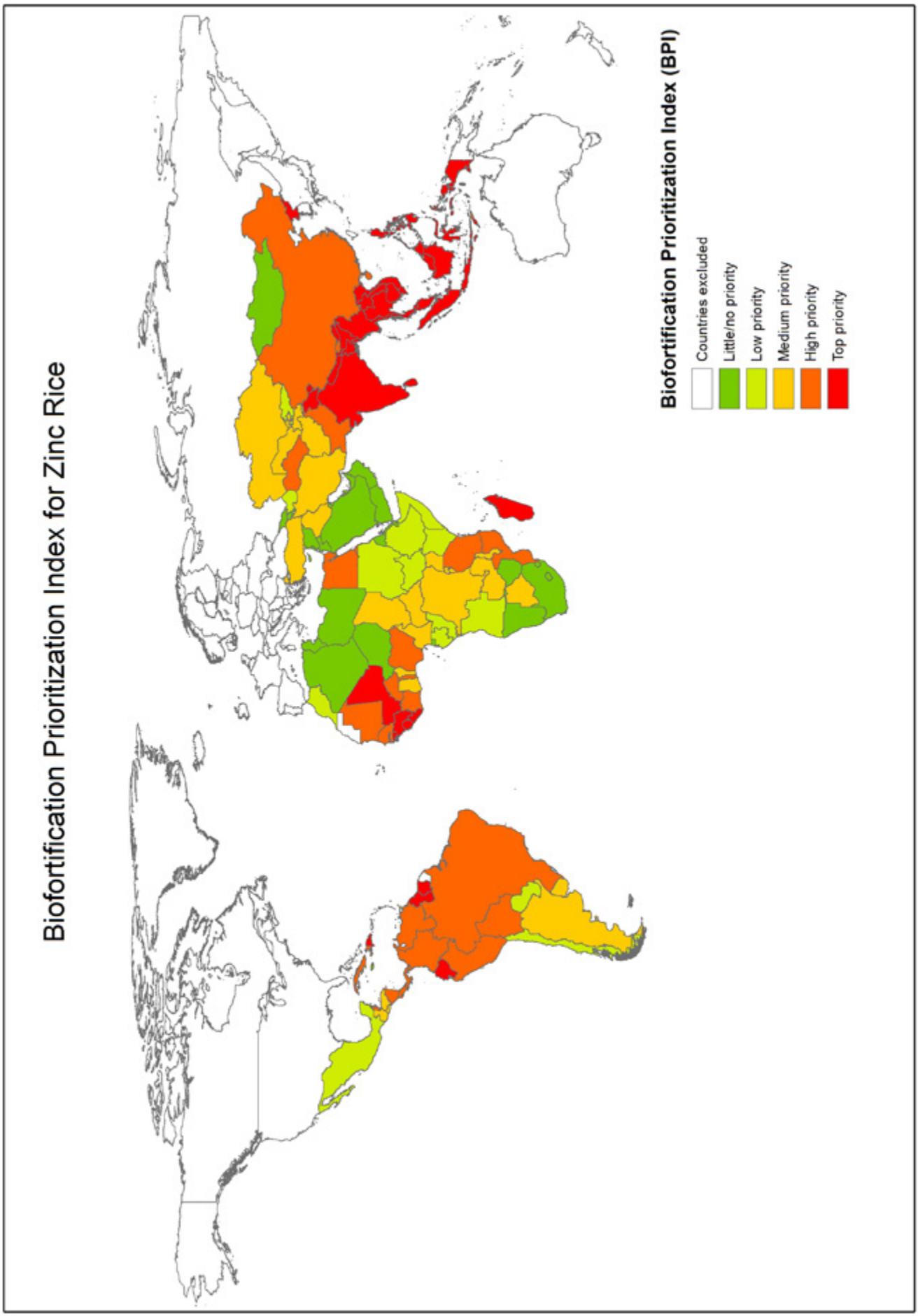
Table 8 presents the top 15 countries that could be suitable candidates for biofortification of rice with zinc in each of the three regions studied. Overall, the BPIs reveal that 12 of the top 15 countries for zinc biofortification of this crop are in Asia; therefore, investments in zinc-rich rice could generate the biggest impact on this continent. Africa is also a promising continent for investments in development and delivery of zinc-rich rice. In global rankings, Sierra Leone and Madagascar are in the top 10 (ranking numbers 7 and 8, respectively), and Liberia and Guinea are in the top 15 (ranking numbers 13 and 14, respectively). In LAC, Guyana and Suriname make it to the top 15 of the global rankings at number 15.

Even though India is number 18 in global rankings, there is significant variation within India as discussed in the context of pearl millet above, especially with regards to rice production. Therefore, a state-level BPI may rank several Indian states ahead of several countries that are ranked higher than India. Overall, rankings reported in Table 8 support ongoing interventions to develop and deliver zinc-rich rice varieties for Bangladesh and Eastern India.

Table 8: BPI Rankings for Top 15 Countries: Rice in Africa, Asia, and LAC

Regional Rank	Africa		Asia		LAC	
1	Sierra Leone	63.7	Cambodia	100.0	Guyana	48.9
2	Madagascar	59.2	Bangladesh	99.5	Suriname	48.9
3	Liberia	50.1	Laos	87.2	Dominican Republic	31.4
4	Guinea	49.7	Myanmar	85.7	Ecuador	30.9
5	Guinea-Bissau	45.6	Viet Nam	74.2	Panama	30.8
6	Gambia	35.7	Indonesia	64.8	Cuba	28.9
7	Comoros	33.5	Sri Lanka	56.9	Nicaragua	28.9
8	Mali	33.2	Philippines	56.6	Peru	28.8
9	Tanzania	25.8	Nepal	55.7	Belize	25.9
10	Côte d'Ivoire	23.0	North Korea	53.7	Bolivia	22.1
11	Senegal	22.7	Thailand	47.2	Costa Rica	20.1
12	Egypt	20.5	India	47.0	Colombia	19.5
13	Mozambique	18.1	Malaysia	32.9	Haiti	18.6
14	Nigeria	17.8	China	25.5	Brazil	17.3
15	Mauritania	17.0	Timor-Leste	20.3	Venezuela	16.9

Figure 6: BPI Map for Rice



Wheat

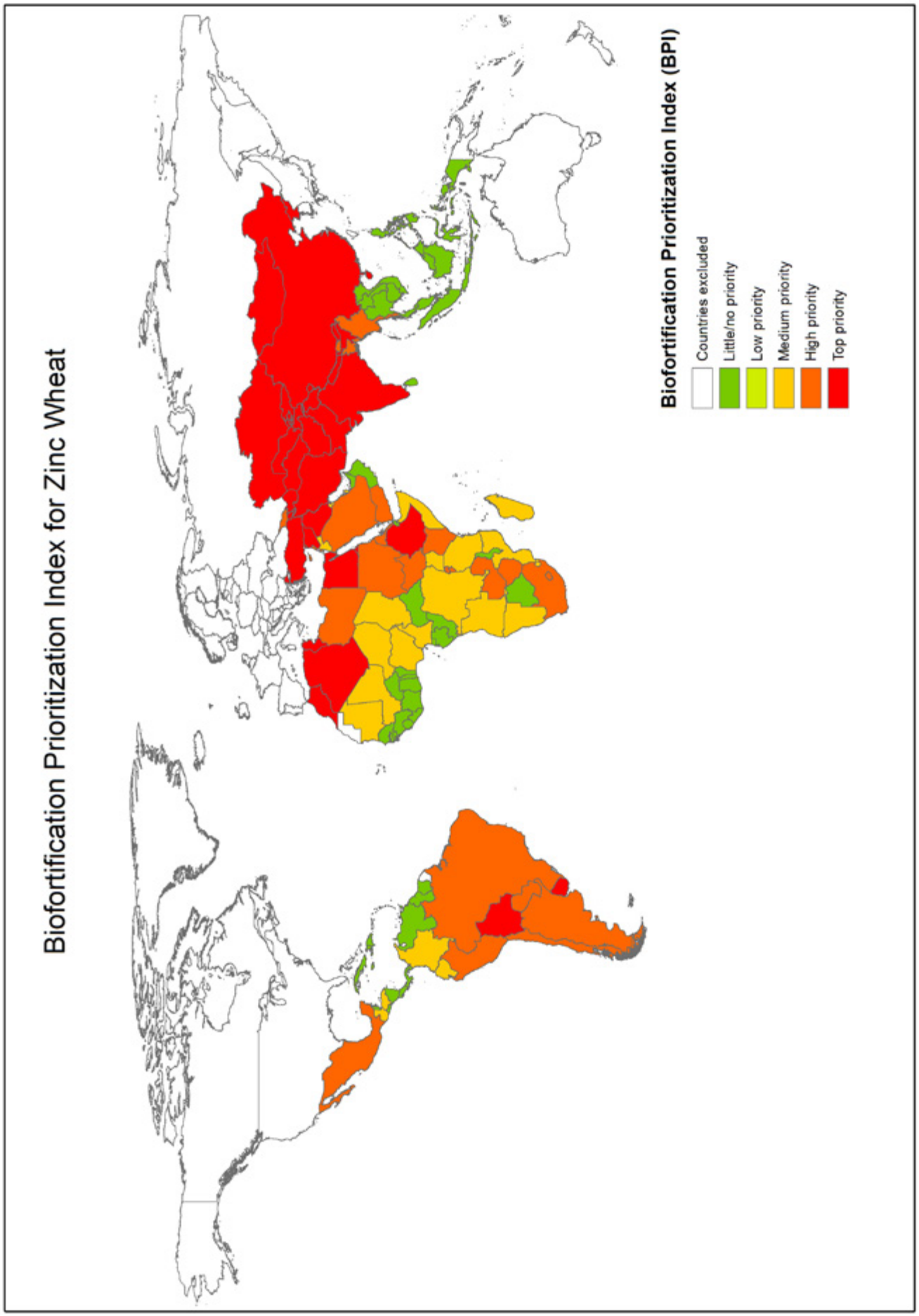
Table 9 presents the top 15 countries that could be suitable candidates for biofortification of wheat with zinc, in each of the three regions studied. Overall, the BPIs reveal that 13 of the top 15 countries are in Asia; therefore, investments in zinc-rich wheat could generate the biggest impact on this continent. Interventions are underway to develop and deliver zinc-rich wheat varieties in Pakistan and India. Central Asian countries exhibit another opportunity for investment for zinc-rich wheat.

In Africa, North African countries are promising candidates with Morocco, Egypt, and Tunisia ranking in the top 20 in global rankings (numbers 12, 14, and 18, respectively). Ethiopia is another suitable candidate on this continent. As in the case of India, Ethiopia is a large country with significant agroecological heterogeneity. Construction of subnational BPIs for Ethiopia, as it was done for the GHI (Schmidt and Dorosh 2009), is therefore warranted.

Table 9: BPI Rankings for Top 15 Countries: Wheat in Africa, Asia, and LAC

Regional Rank	Africa		Asia		LAC	
1	Morocco	63.0	Tajikistan	100.0	Uruguay	44.2
2	Egypt	60.3	Turkmenistan	98.5	Bolivia	38.8
3	Ethiopia	54.4	Azerbaijan	95.0	Argentina	37.3
4	Tunisia	48.6	Afghanistan	93.4	Paraguay	25.9
5	Algeria	44.0	Pakistan	93.2	Chile	25.4
6	Rwanda	30.3	Kazakhstan	85.5	Brazil	23.7
7	South Africa	29.9	Uzbekistan	82.2	Peru	23.0
8	Eritrea	27.5	Turkey	79.0	Mexico	21.4
9	Lesotho	26.7	India	77.9	Guatemala	9.8
10	Kenya	23.6	Iraq	75.2	Ecuador	6.2
11	Zambia	21.5	Nepal	75.0	Honduras	5.7
12	Burundi	18.3	Syria	61.0	Colombia	3.6
13	Libya	18.1	Iran	60.0		
14	Sudan	16.5	Armenia	58.0		
15	Zimbabwe	12.7	Kyrgyzstan	55.7		

Figure 7: BPI Map for Wheat



Global Comparisons, by Crop

Table 10 presents a global summary of Tables 3–9. This summary will be useful when comparing the global rankings from unweighted BPIs to the weighted BPIs presented in Tables 11 and 12. Overall, Table 10 highlights that biofortification of cassava, maize, and sweet potato with vitamin A and beans and pearl millet with iron is likely to generate the biggest impact in African countries; whereas biofortification of rice and wheat with zinc could benefit Asian countries the most.

At first sight, LAC countries (other than Haiti, in the case of both sweet potato and beans) do not render themselves for investment in biofortification. It should be noted, however, that unlike in African and Asian countries, there is not one major staple crop in this region. A food basket approach, i.e., biofortification of all key crops, is therefore warranted. Moreover, national-level data may hide regions in LAC countries where consumption and production of these crops, as well as micronutrient deficiency, are rampant. Therefore, sub-national BPIs should be generated, especially for larger LAC countries.

Table 10: Global BPI Ranking of Top 15 Countries, by Crop

Global Rank	Cassava	Maize	Sweet Potato	Beans	Pearl Millet	Rice	Wheat
1	Mozambique	Malawi	Angola	Rwanda	Niger	Cambodia	Tajikistan
2	Angola	Benin	Burundi	Benin	Gambia	Bangladesh	Turkmenistan
3	Ghana	Zambia	Uganda	Tanzania	Burkina Faso	Laos	Azerbaijan
4	Liberia	Kenya	Mozambique	Burundi	Chad	Myanmar	Afghanistan
5	Benin	Mozambique	Rwanda	Myanmar	Senegal	Viet Nam	Pakistan
6	Central African Republic	Angola	Tanzania	Togo	Nigeria	Indonesia	Kazakhstan
7	DR Congo	Burkina Faso	Sierra Leone	Haiti	Namibia	Sierra Leone	Uzbekistan
8	Sierra Leone	Zimbabwe	Madagascar	Uganda	Guinea-Bissau	Madagascar	Turkey
9	Côte d'Ivoire	Timor-Leste	Guinea	Angola	Uganda	Sri Lanka	India
10	Zambia	Mali	Haiti	Kenya	Nepal	Philippines	Iraq
11	Malawi	Togo	Kenya	Brazil	India	Nepal	Nepal
12	Congo	Tanzania	Mali	Cameroon	Ghana	North Korea	Morocco
13	Togo	Ghana	Laos	Nicaragua	Togo	Liberia	Syria
14	Madagascar	Gambia	Benin	Chad	Sierra Leone	Guinea	Egypt
15	Guinea	Lesotho	Timor-Leste	Malawi	Myanmar	Guyana	Iran

4.2. Population- and Area-Weighted BPIs

As discussed in section 2.3 above, crop-specific BPIs presented in section 4.1 do not take into consideration factors such as the size of the target population and crop area in the countries. In this subsection, we present two weighted versions of the crop-specific BPI, both calculated by using equation 8 from above. We compare the rankings obtained from the weighted BPI to the unweighted ones presented in Table 10.

Population-Weighted BPIs

The population-weighted, crop-specific BPI considers the target populations for biofortification investments. These are women of childbearing age (15–49 years) and children age 6–59 months. For this version of the BPI, the country weight is calculated as the country's target population share in the total global target population. "Global" refers to the 127 countries in the three regions of focus. The estimates were obtained from the 2012 World Development Indicators (World Bank 2012).

As expected, the BPIs look very different once population weights are taken into account. Comparison of the top 15 countries for unweighted BPIs presented in Table 10 to population-weighted BPIs presented in Table 11 reveals that over half of the countries are similar for pearl millet and wheat, whereas the lists are significantly dissimilar for several crops, especially for maize and cassava. In Table 11, the top 5 places for each of the crops are populated by those countries with the largest populations (China, India Indonesia, Bangladesh, and Pakistan). For instance, Rwanda, which ranks first for beans according to the unweighted BPI, falls to number 28 with the population-weighted BPI. This is because target population-wise, Rwanda is almost 90 times smaller than India. Similarly, according to the unweighted BPI, Malawi ranks first for maize; however, when adjusted for population size, it falls to number 21. Among the LAC countries, Brazil and Mexico surface as potential countries for biofortification investment. The maps for the population-weighted BPIs by crop and regions can be found in Appendix 2.

Table 11: Global Ranking of Top 15 Countries by Crop, Population-Weight Adjusted

Global Rank	Cassava	Maize	Sweet Potato	Beans	Pearl Millet	Rice	Wheat
1	India	India	China	India	India	India	India
2	China	China	India	China	China	China	China
3	Nigeria	Indonesia	Nigeria	Indonesia	Nigeria	Indonesia	Pakistan
4	Indonesia	Nigeria	Indonesia	Pakistan	Pakistan	Bangladesh	Bangladesh
5	DR Congo	Ethiopia	Ethiopia	Brazil	Ethiopia	Viet Nam	Ethiopia
6	Philippines	Pakistan	Bangladesh	Bangladesh	Uganda	Pakistan	Egypt
7	Tanzania	Bangladesh	Tanzania	Ethiopia	Niger	Philippines	Turkey
8	Brazil	Mexico	Uganda	Tanzania	Tanzania	Nigeria	Brazil
9	Viet Nam	DR Congo	DR Congo	Myanmar	Myanmar	Thailand	Iran
10	Uganda	Philippines	Viet Nam	DR Congo	Nepal	Myanmar	Afghanistan
11	Thailand	Kenya	Kenya	Kenya	Burkina Faso	Brazil	Nigeria
12	Mozambique	Brazil	Mozambique	Mexico	Kenya	Egypt	Mexico
13	Kenya	Tanzania	Pakistan	Uganda	Ghana	DR Congo	Nepal
14	Ghana	Egypt	Egypt	Philippines	Yemen	Tanzania	Uzbekistan
15	Madagascar	Viet Nam	Brazil	Thailand	Chad	Nepal	Kenya
% countries in unweighted BPI top 15	27%	13%	20%	33%	53%	40%	53%

Area-Weighted BPI

The area-weighted index gives more weight to the BPI of those countries that have relatively larger cultivated crop land areas. For each crop, the area-weighted BPI was calculated as the country's share of cultivated land area in global cultivated land area for the respective crop. As with the population-weighted index, "global" refers to the 127 countries in the three study regions.

The picture for the area-weighted BPIs is also different from the unweighted BPIs, although the results are not as significantly different as what we observed with the population-weighted indices. Comparison of the top 15 countries for unweighted BPIs presented in Table 10 to area-weighted BPIs presented in Table 12 reveals that for all crops except maize, 60 to 73 percent of the countries are similar, though the rankings are reshuffled. Some new countries, however, make it to the top 15 when area weights are accounted for. Most notable ones include countries with large areas, including: Nigeria for cassava; China, Brazil, and Mexico for maize; China for sweet potato and wheat; and India for beans and rice. The maps for the area-weighted BPIs can be found in Appendix 2.

Table 12: Global ranking of Top 15 Countries by Crop, Area-Weight Adjusted

Global Rank	Cassava	Maize	Sweet Potato	Beans	Pearl Millet	Rice	Wheat
1	Nigeria	China	China	India	Niger	India	India
2	DR Congo	Mexico	Uganda	Brazil	India	Bangladesh	Kazakhstan
3	Angola	Brazil	Nigeria	Myanmar	Nigeria	Indonesia	China
4	Mozambique	Malawi	Tanzania	Tanzania	Burkina Faso	China	Pakistan
5	Ghana	India	Angola	Uganda	Chad	Myanmar	Turkey
6	Tanzania	Tanzania	Burundi	Mexico	Senegal	Viet Nam	Iran
7	Brazil	Kenya	Mozambique	Angola	Uganda	Thailand	Afghanistan
8	Benin	Nigeria	Rwanda	Kenya	Namibia	Cambodia	Morocco
9	Indonesia	Mozambique	Madagascar	Rwanda	Gambia	Philippines	Argentina
10	Central African Republic	South Africa	Haiti	Benin	Nepal	Madagascar	Uzbekistan
11	Côte d'Ivoire	Angola	Guinea	Togo	Ethiopia	Nepal	Iraq
12	Thailand	Indonesia	Ghana	Burundi	Guinea	Laos	Syria
13	Madagascar	Zambia	Indonesia	Cameroon	Tanzania	Sri Lanka	Ethiopia
14	Uganda	Zimbabwe	Ethiopia	North Korea	Pakistan	Brazil	Turkmenistan
15	Zambia	Ethiopia	Viet Nam	Guatemala	Zimbabwe	Guinea	Algeria
% countries in unweighted BPI top 15	60%	47%	60%	73%	60%	73%	73%

5. DISCUSSION

The BPI developed and presented in this paper aims to help inform investments in biofortification. This index, however, should not be taken as a one-stop shop for making a decision about whether to invest in biofortification for a country-crop-micronutrient combination. Despite the authors' due diligence in creating an index that takes into consideration a myriad of variables, it still suffers from several limitations.

The main limitation of the BPI is that it draws on national-level data, which does not allow for investigation of variations in production, consumption, and micronutrient deficiency within a country. It is likely that the BPI overlooks countries with promising "pockets" for biofortification investment. It is also likely that even though a country may exhibit high levels in all three indices, areas where the crop is produced and consumed and areas where there is significant micronutrient deficiency may not overlap. Furthermore, larger countries (e.g., India, China, Egypt, Nigeria, Brazil, and Ethiopia) tend to have significant regional differences in agroecology and related crop production/consumption patterns, as well as in income and hence associated micronutrient deficiency levels. For such countries, regional or state-level BPIs may need to be further investigated.

In addition, the national-level consumption figures, which average consumption of both rural and urban residents, could be downward biased for rural people who are more likely to consume more staple crops than their urban counterparts. Moreover, for some inferior staples, such as cassava or pearl millet, national per-capita consumption levels could hide the fact that the poor (and hence those suffering from hidden hunger) consume high amounts of staple crops than the national average. It could also be true that for some staples with higher income elasticity (e.g., rice), those suffering from hidden hunger may actually consume less than the national average suggests. Additionally, it is possible that consumption figures are upward biased because the target populations under consideration (especially children 6–59 months) consume less than the average person.

Another limitation of the BPI is that it does not explicitly take into consideration the cost (breeding, multiplication, delivery, marketing, and awareness campaigns) and benefits (number of DALYs saved) of biofortification. To account for this, we consider that the micronutrient deficiency subindex serves as a proxy for the potential benefits of biofortification investments (the higher this index, the more DALYs can be saved). In addition, the production and consumption indices implicitly account for investment costs (the higher the production and consumption levels of a crop, the lower the costs of delivery and the more cost-effective the behavior change campaigns would be).

The BPI also does not take into account factors that may alleviate or exacerbate nutrition outcomes (e.g., water quality, sanitation, prevalence of infectious diseases, coverage of other nutrition interventions), nor does it consider dynamic factors such as climate change or income and population growth, all of which may affect consumption and production of these staple crops, as well as micronutrient deficiency levels.

Finally, the current BPI has some data limitations. For many countries, the main data source used, FAOSTAT, was incomplete for the set of variables needed to create the BPI. This required obtaining data from other secondary sources, which often differ in terms of the time period used for data collection. Overall, FAOSTAT data are not considered to be reliable by some researchers; however, it is one of the few datasets that contains consumption and production data for almost all countries in the world, and that is why it was used for this study.

Another type of data limitation is the definition of the crop data that is available for use. FAOSTAT data on dry beans, for instance, aggregate all kinds of beans (not necessarily the biofortified common beans *phaseolus vulgaris*). In addition, FAOSTAT data on millet include all kinds of millet, including pearl millet. Expert breeders have confirmed that in the case of pearl millet, the majority of millet data are from pearl millet, the most widely grown millet in the world (Wolfgang Pfeiffer, personal communication, 2013). This is also true for beans; although in the case of India, Nepal, and Myanmar, "beans" often include a variety of beans, such as *Vigna unguiculata*, in addition to the common beans (Steve Beebe, personal communication, 2013).

6. CONCLUSIONS, PROGRAMMATIC IMPLICATIONS, AND FUTURE RESEARCH

As evidence builds proving the nutritional efficacy and effectiveness, as well as the cost-effectiveness, of biofortification for alleviating micronutrient deficiencies, various stakeholders will be increasingly interested in investing in this intervention. Information is needed on which country-crop-micronutrient combinations would constitute the "best bets" for investing in biofortification for maximum public health impact.

To help fill this gap, we developed the Biofortification Prioritization Index (BPI), which aims to rank countries in terms of their potential for biofortification of seven staple crops (cassava, maize, sweet potato, beans, pearl millet, rice, and wheat) with three key micronutrients (vitamin A, iron, and zinc) that are essential for human health. The BPI can serve as a first filter to eliminate those countries where biofortification does not seem appropriate either because the populations do not suffer from micronutrient deficiency or the target crops are not produced or consumed in sufficient quantities. To guide investment and funding decisions, several other criteria should be taken into consideration. These include, but are not limited to, the suitability of available varieties, costs of biofortification, technical and institutional environments of the country, and availability and cost-effectiveness of complementary interventions.

To develop this index we used national-level production, consumption, and micronutrient deficiency data compiled from various sources (FAO, WHO, USDA, and World Bank) and a heuristic approach akin to those employed to develop similar preceding indices (e.g., Human Development Index [HDI] and Global Hunger Index [GHI]). We generated two kinds of indices: (1) two weighted BPIs that take into consideration either target population or crop land area of a country relative to the rest of the world and (2) an unweighted BPI.

Overall the results reveal that crops biofortified with vitamin A, namely maize, cassava, and sweet potato, should be introduced primarily in African countries; whereas crops biofortified with zinc, namely wheat and rice, should be introduced in Asia. For iron biofortified beans, several countries in Africa and some in LAC reveal high return-on-investment potential. Finally for iron biofortified pearl millet, Africa (especially West Africa) and some countries in South Asia constitute suitable candidate sites for investment. Comparison of the unweighted and the weighted BPIs reveals that these two kinds of BPIs could be useful for stakeholders looking to achieve different objectives. Population-weighted BPIs could be used by stakeholders whose mandate is to reach as many beneficiaries as possible, whereas area-weighted BPI could benefit those whose aim is to maximize area allocated to biofortified crops. Overall, the findings of this exercise are in line with the currently implemented and planned biofortification interventions, although several BPIs have surfaced that suggest new avenues for exploration.

The main limitation of the BPI—apart from the lack of data on cost-effectiveness—is that the national-level data used to generate this index may overlook investment opportunities that could generate high levels of impact. Future research aims to remedy this shortcoming and improve the BPI as follows:

(1) Using regional or state-level data, especially for larger countries, to generate within-country BPIs. These data will be obtained from the agricultural and health ministries, Demographic Health Surveys (DHS), and Living Standard Measurement Study Surveys (LSMS), among other sources.

(2) Using household-level production, consumption, and micronutrient intake (deficiency) data (from those sources identified in (1) and others) and *ex ante* simulation modeling tools to develop detailed investment opportunity maps for those countries identified to be high potential by the current BPI. This modeling exercise will also include temporal aspects (looking at climate change, population, and income growth), as well as coverage of other micronutrient interventions.

For the time being, however, the BPI presented in this paper is a useful tool for highlighting those countries that may convey significant reductions in micronutrient deficiency through biofortification.

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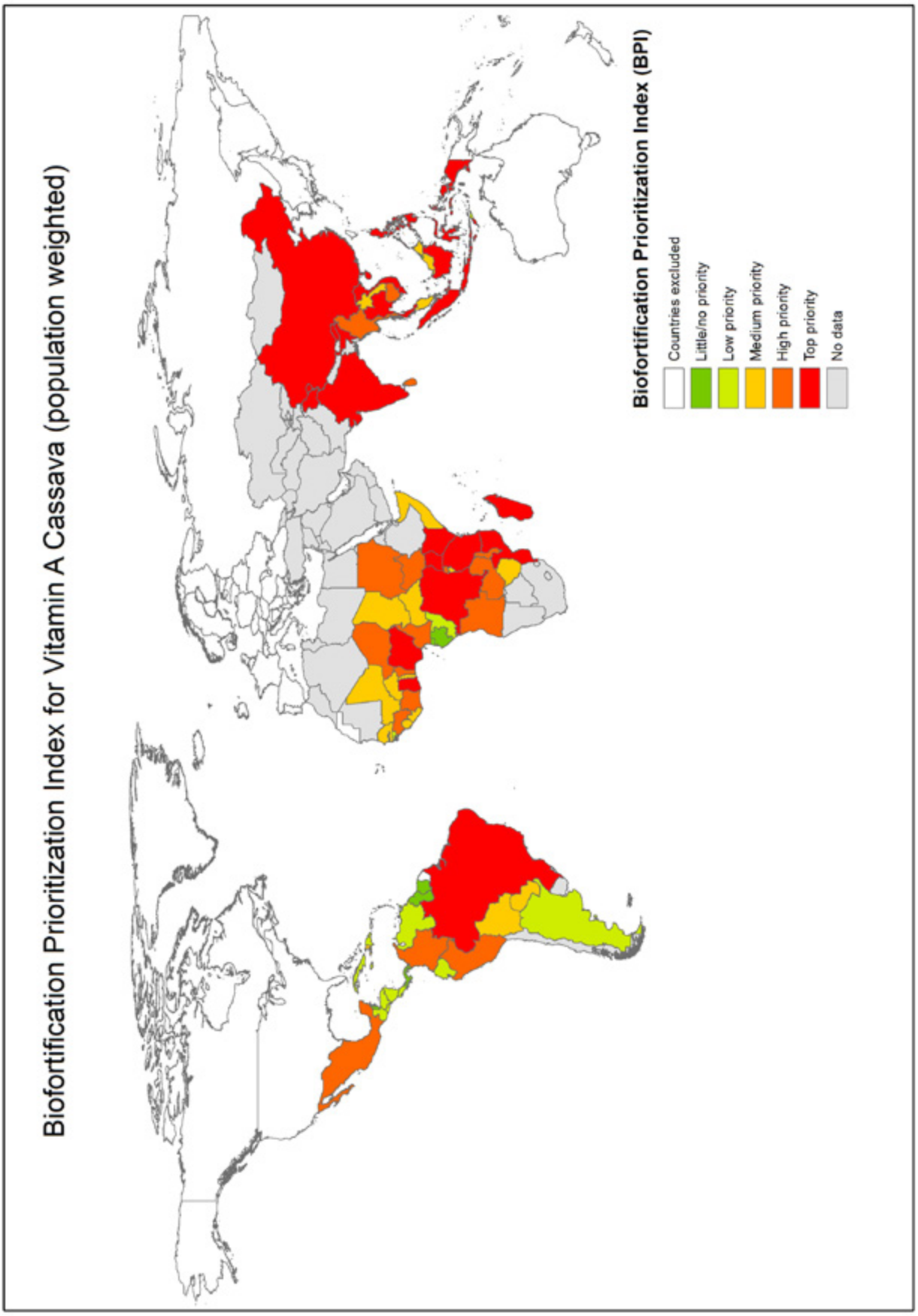
APPENDIX 1: LIST OF COUNTRIES INCLUDED IN BPI

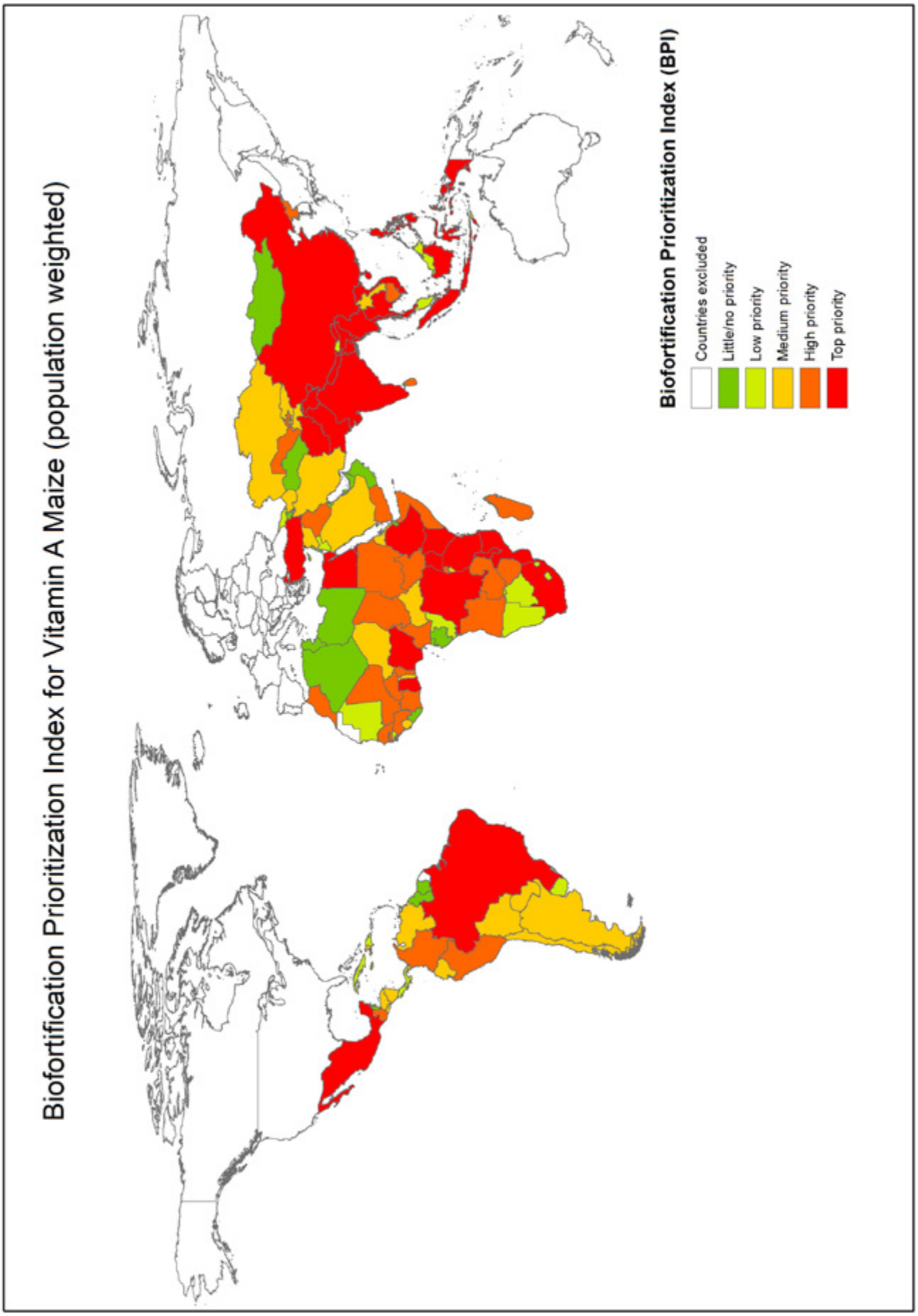
Afghanistan	Ethiopia	Nigeria
Algeria	Gabon	North Korea
Angola	Gambia	Occupied Palestinian Territory
Antigua and Barbuda	Georgia	Oman
Argentina	Ghana	Pakistan
Armenia	Grenada	Panama
Azerbaijan	Guatemala	Paraguay
Bahrain	Guinea	Peru
Bangladesh	Guinea-Bissau	Philippines
Barbados	Guyana	Qatar
Belize	Haiti	Rwanda
Benin	Honduras	Saint Kitts and Nevis
Bhutan	India	Saint Lucia
Bolivia	Indonesia	Saint Vincent and the Grenadines
Botswana	Iran	Saudi Arabia
Brazil	Iraq	Senegal
Brunei Darussalam	Jamaica	Sierra Leone
Burkina Faso	Jordan	Singapore
Burundi	Kazakhstan	Somalia
Cambodia	Kenya	South Africa
Cameroon	Kuwait	Sri Lanka
Cape Verde	Kyrgyzstan	Sudan (former)
Central African Republic	Laos	Suriname
Chad	Lebanon	Swaziland
Chile	Lesotho	Syria
China	Liberia	Tajikistan
Colombia	Libya	Tanzania
Comoros	Madagascar	Thailand
Congo	Malawi	Timor-Leste
Costa Rica	Malaysia	Togo
Côte d'Ivoire	Mali	Trinidad and Tobago
Cuba	Mauritania	Tunisia
Cyprus	Mauritius	Turkey
Democratic Republic of the Congo	Mexico	Turkmenistan
Djibouti	Mongolia	Uganda
Dominica	Morocco	United Arab Emirates
Dominican Republic	Mozambique	Uruguay
Ecuador	Myanmar	Uzbekistan
Egypt	Namibia	Venezuela
El Salvador	Nepal	Viet Nam
Equatorial Guinea	Nicaragua	Yemen
Eritrea	Niger	Zambia
		Zimbabwe

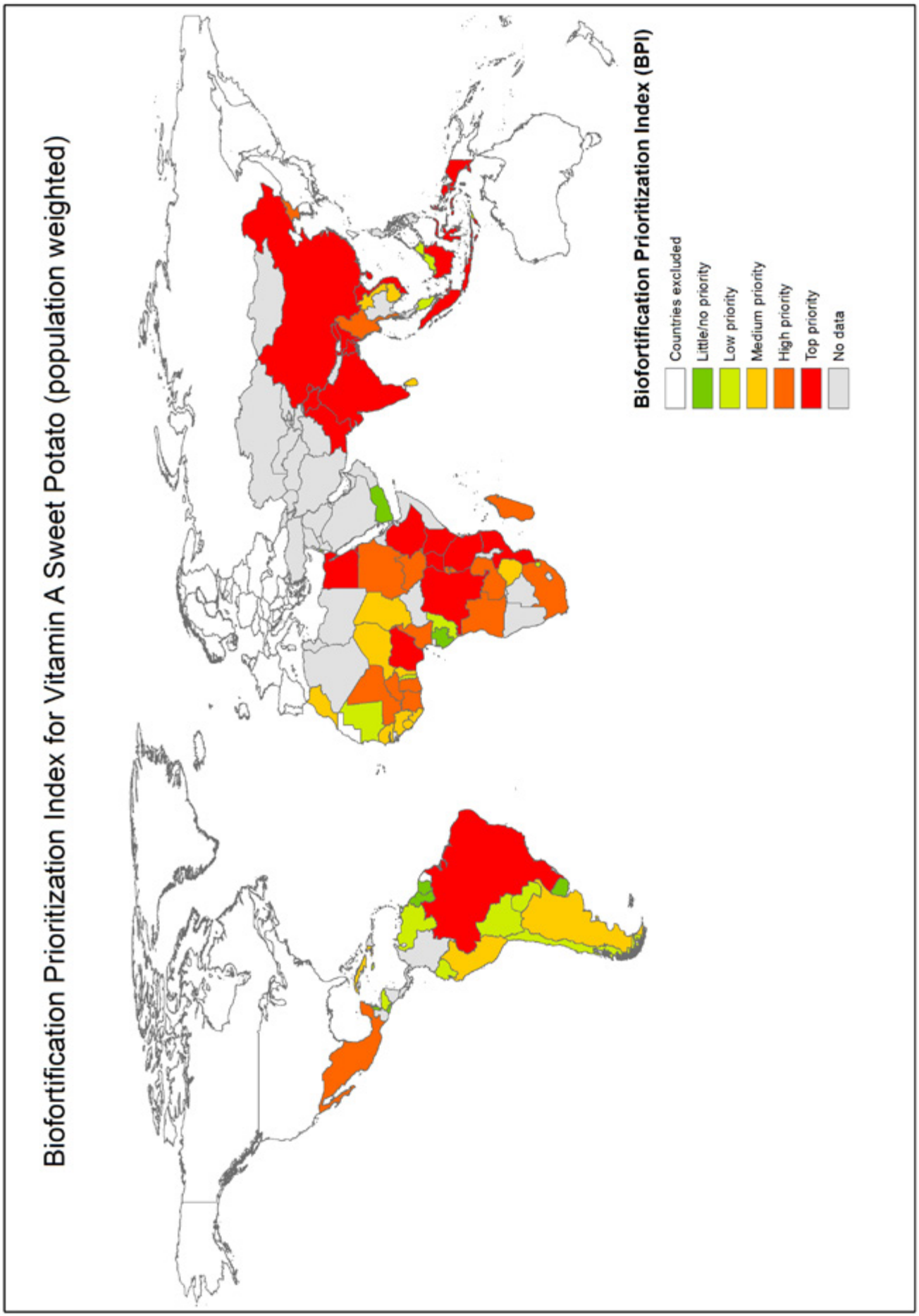
APPENDIX 2: WEIGHTED BPI MAPS BY CROP AND REGION

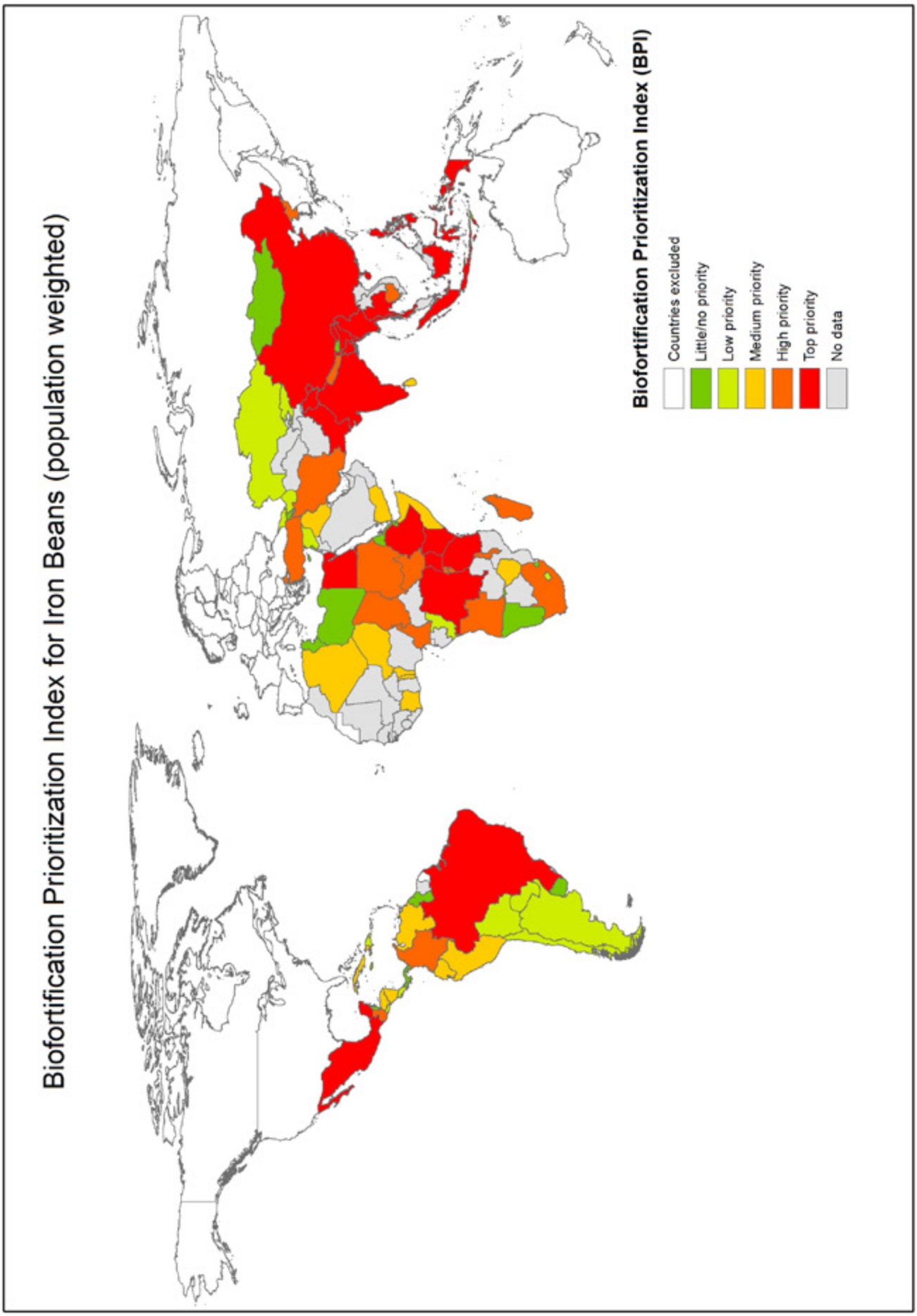
Population-Weighted BPI Maps

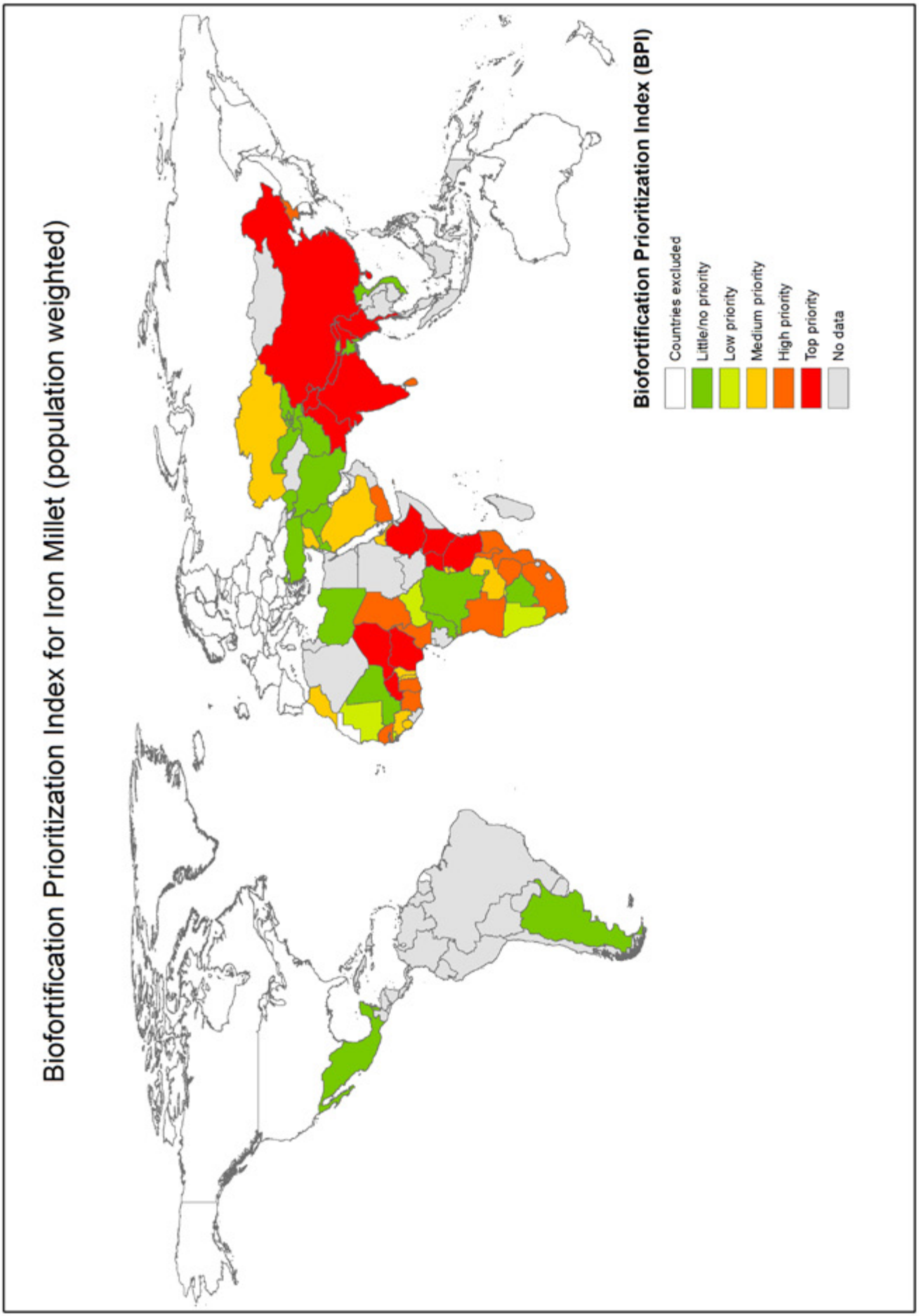
Cassava

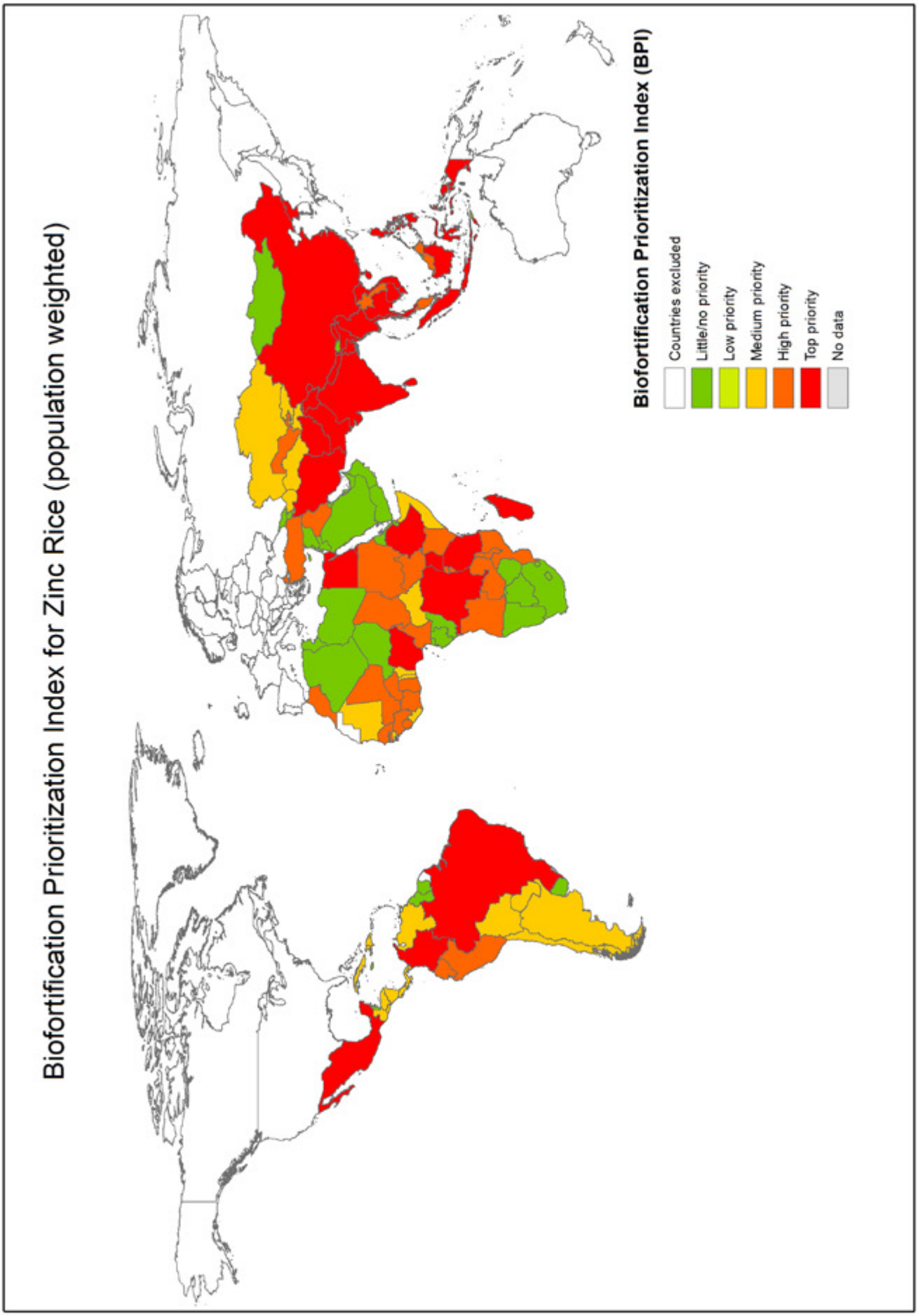


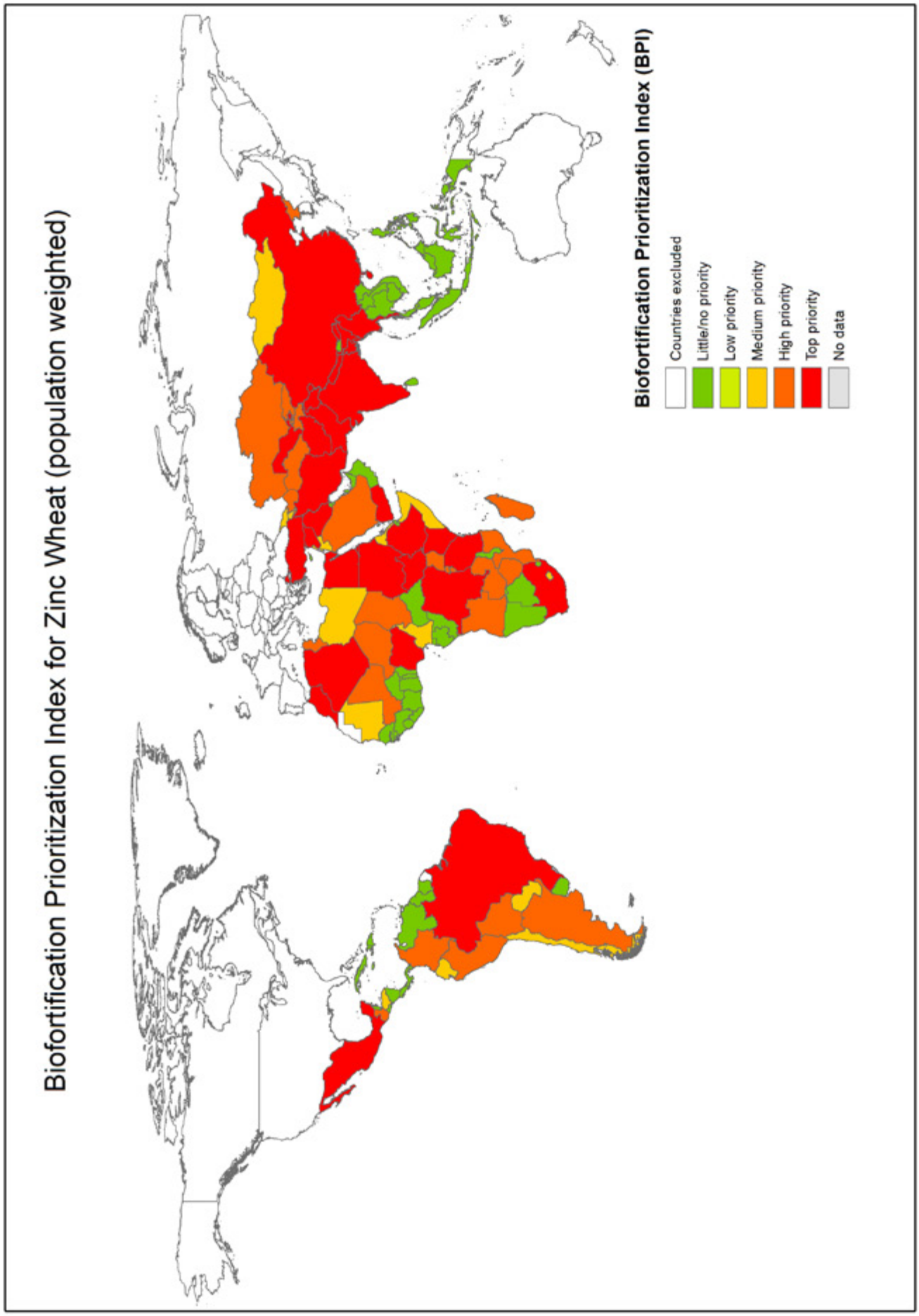

Biofortification Prioritization Index for Vitamin A Maize (population weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority


Biofortification Prioritization Index for Vitamin A Sweet Potato (population weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority
No data


Biofortification Prioritization Index for Iron Beans (population weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority
No data

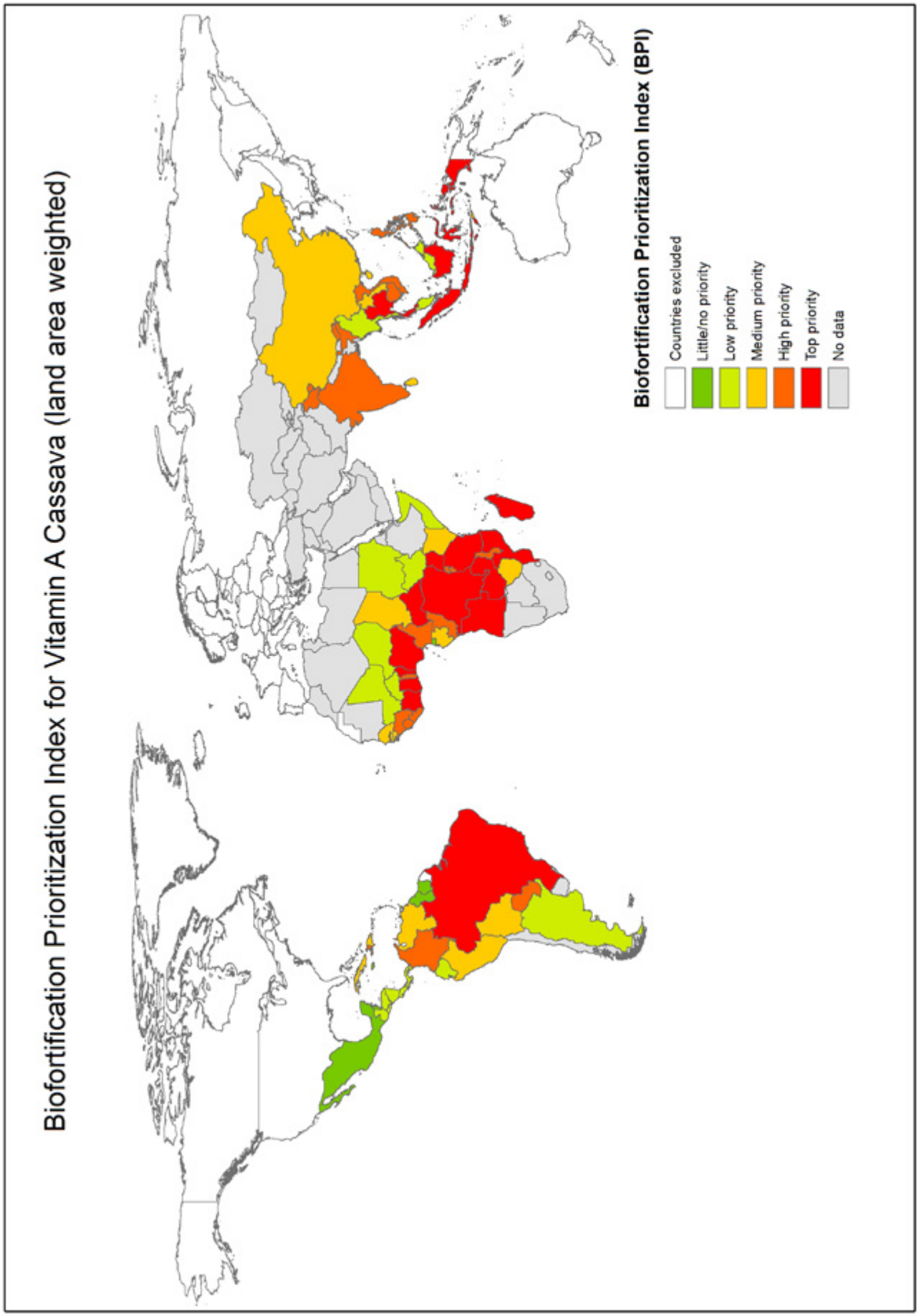

Biofortification Prioritization Index for Iron Millet (population weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority
No data

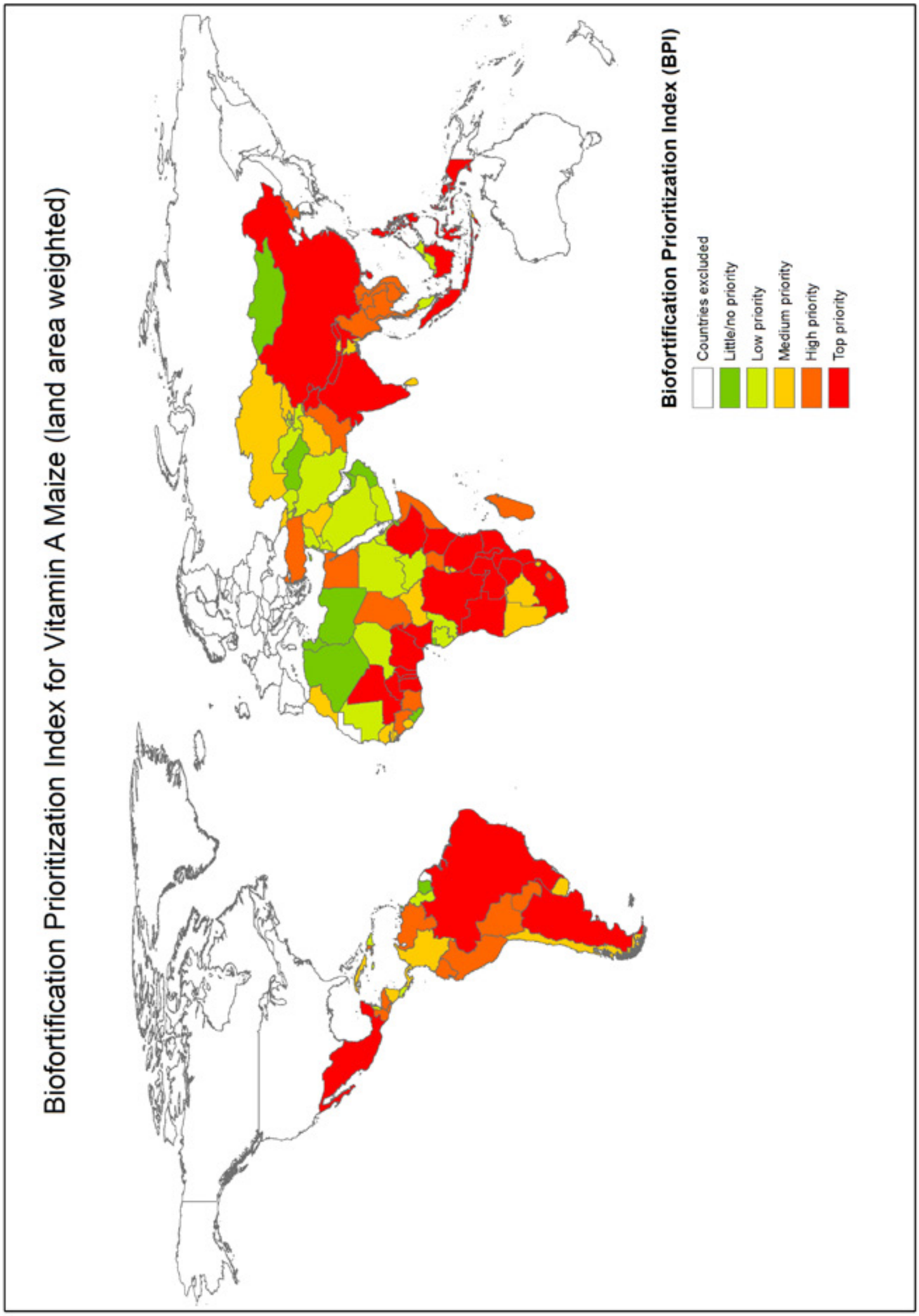

Biofortification Prioritization Index for Zinc Rice (population weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority
No data

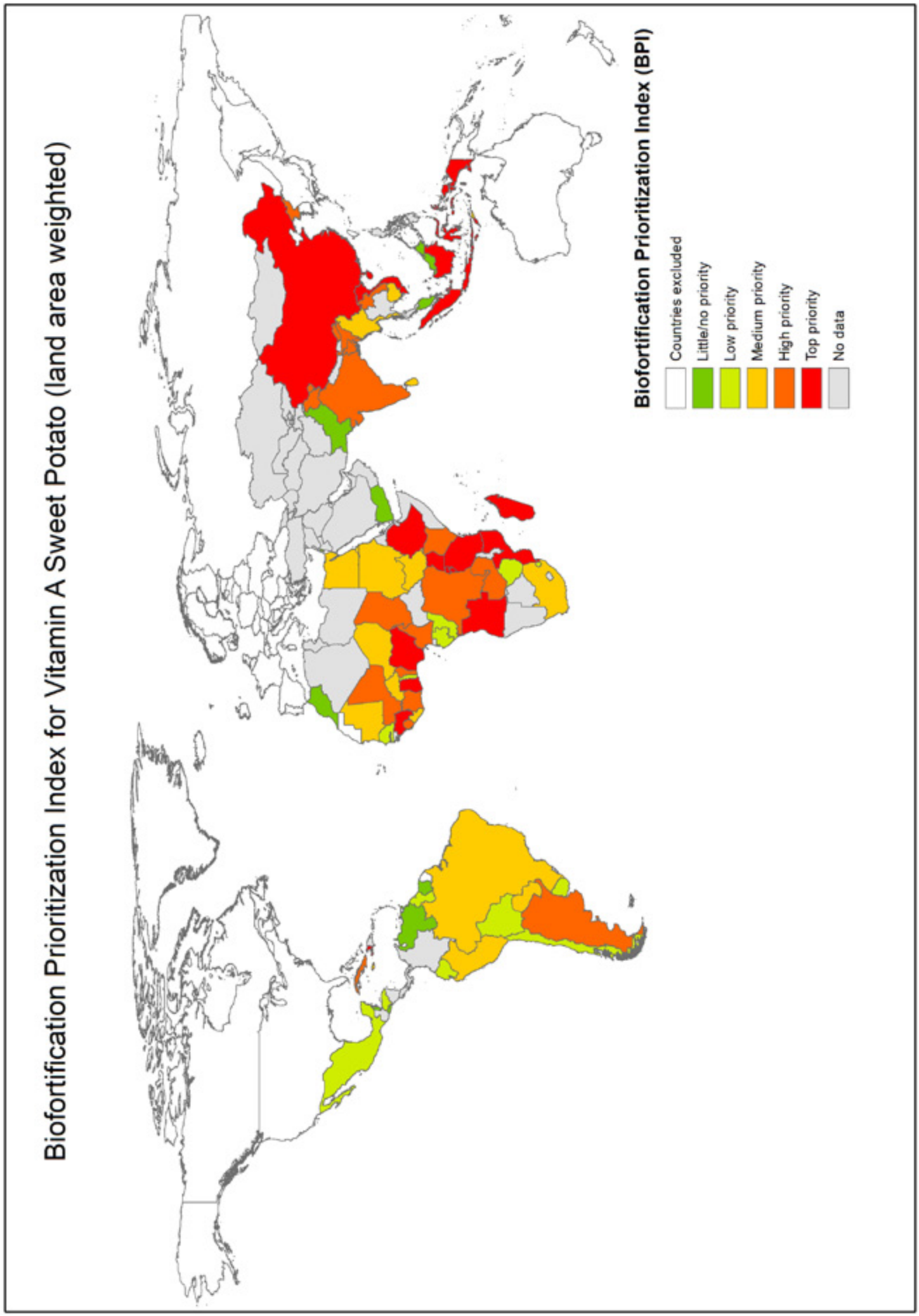

Biofortification Prioritization Index for Zinc Wheat (population weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority
No data

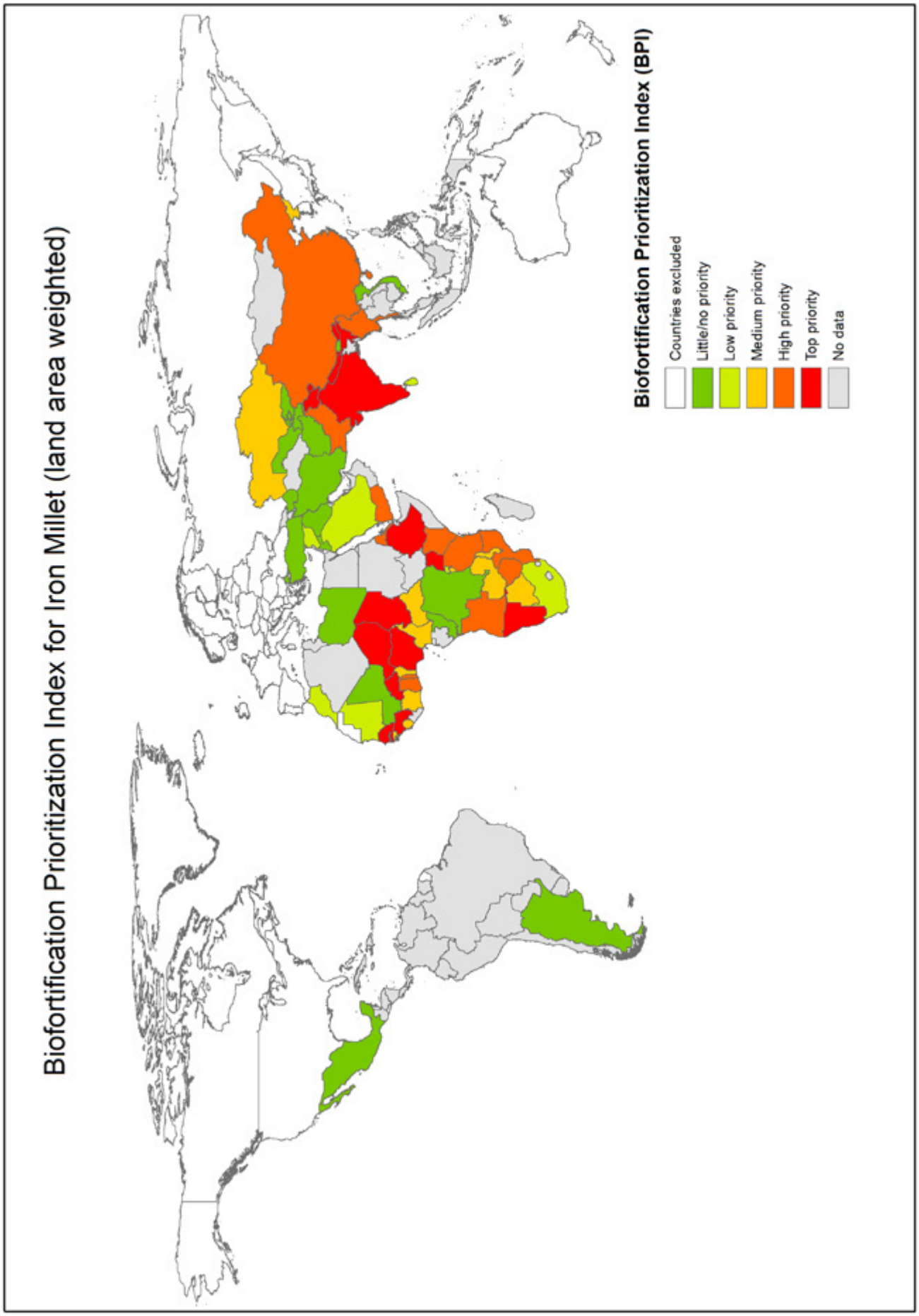
Area-Weighted BPI Maps

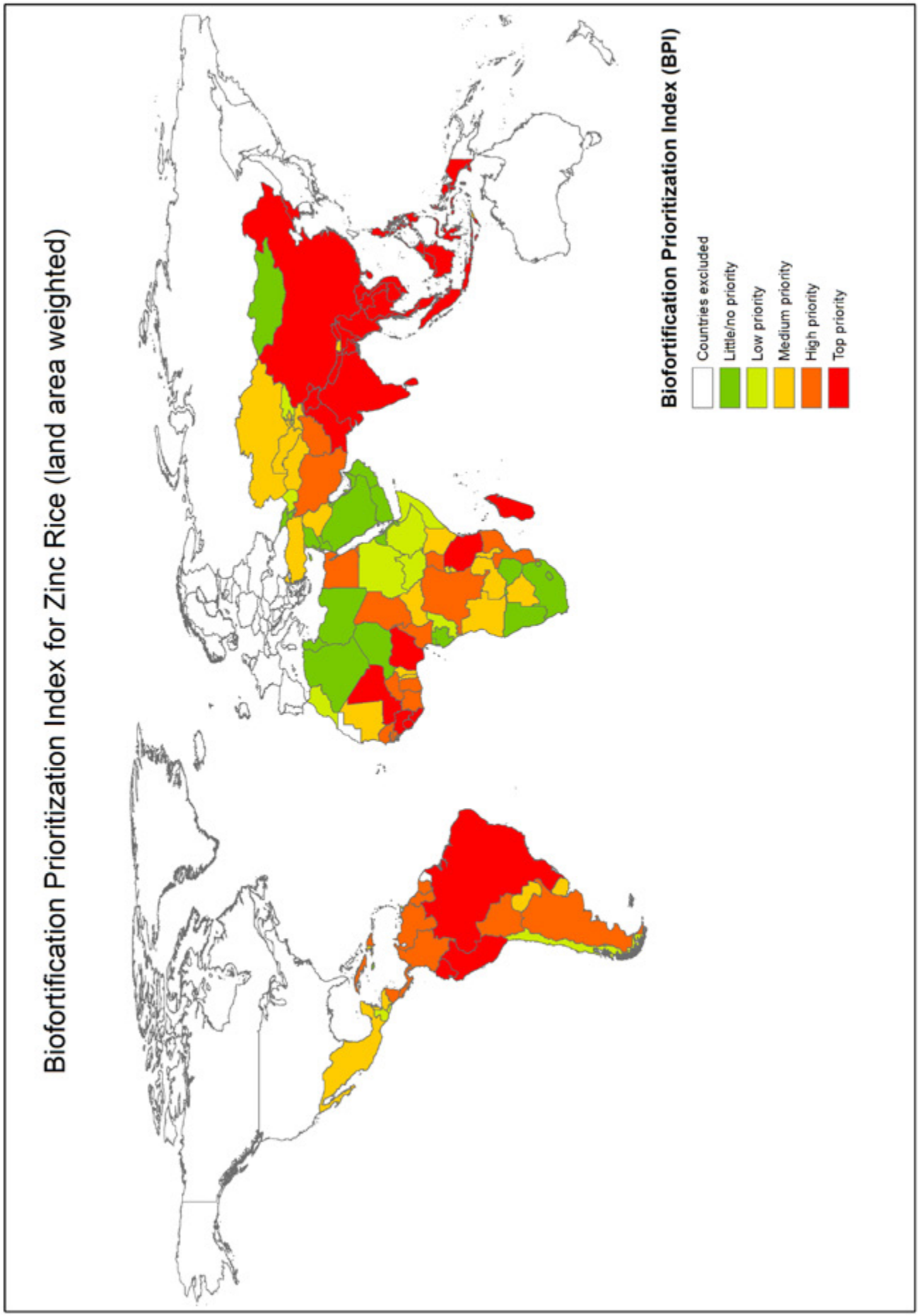
Cassava

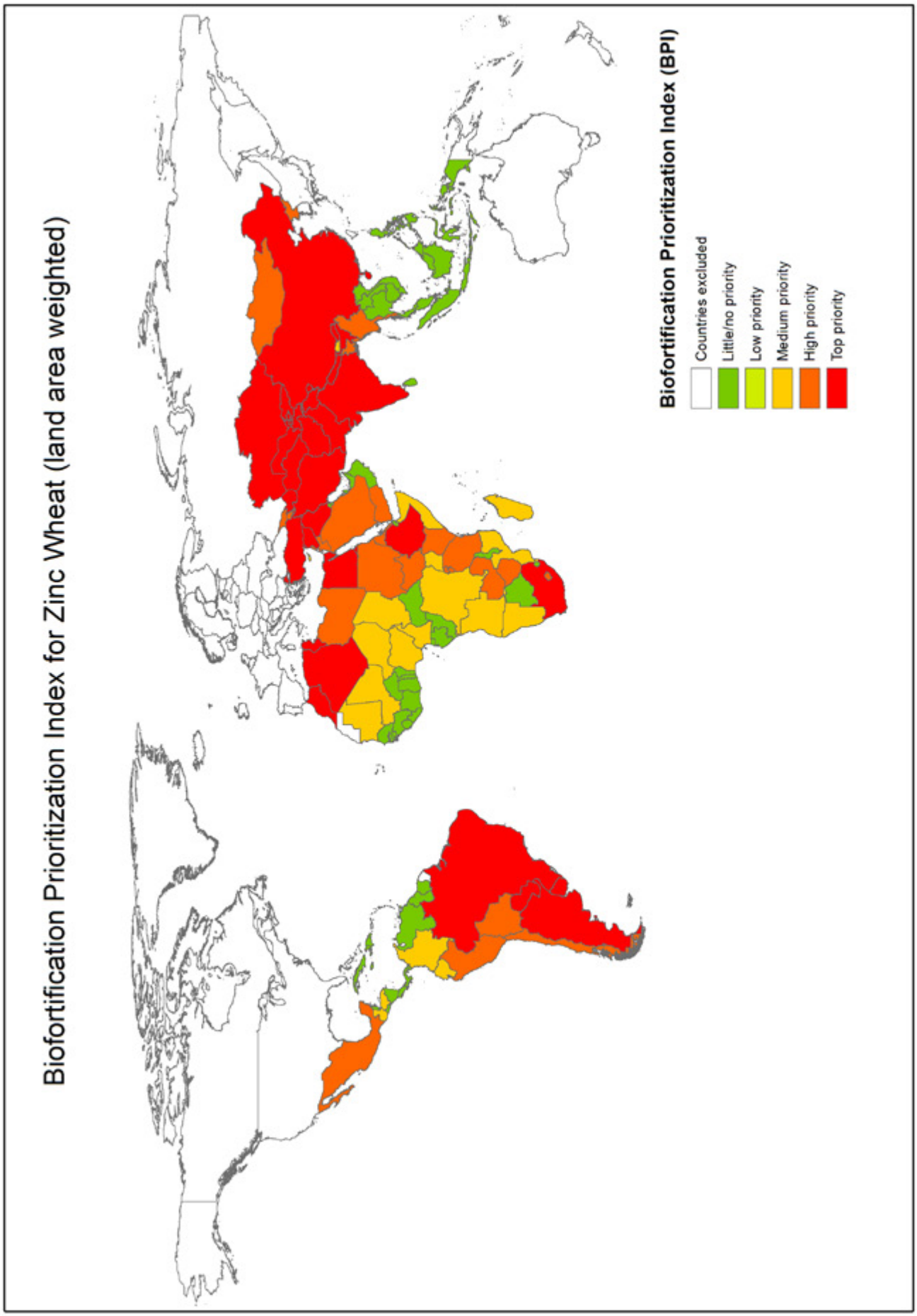



Biofortification Prioritization Index for Vitamin A Maize (land area weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority


Biofortification Prioritization Index for Vitamin A Sweet Potato (land area weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority
No data


Biofortification Prioritization Index for Iron Millet (land area weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority
No data


Biofortification Prioritization Index for Zinc Rice (land area weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority


Biofortification Prioritization Index for Zinc Wheat (land area weighted)
Biofortification Prioritization Index (BPI)
Countries excluded
Little/no priority
Low priority
Medium priority
High priority
Top priority