World Vegetable Center

POSITION PAPER

Vegetables and Climate Change

Pathways to Resilience

MARCH 2020

1. Introduction

Micronutrient deficiencies are a significant public health concern, affecting an estimated 2 billion people worldwide (Ritchie and Roser 2017). This represents a major burden on the social and economic development in low- and medium-income countries, with hundreds of millions of children stunted, tens of millions of women of reproductive age suffering serious deficiencies of vitamins and minerals, and more than 1 billion people, children, adolescents and adults alike, now overweight or obese. Nelson et al. (2018) predicted that many regions will continue to have critical micronutrient inadequacies using a range of biophysical and socioeconomic scenarios towards 2050. These findings indicate that the greatest food security challenge in 2050 will be providing nutritious diets rather than adequate calories. In this regard, ensuring sufficient dietary intake of fruit and vegetables is critical to prevent and mitigate micronutrient deficiencies, as well as to tackle non-communicable diseases (Yip et al. 2019). Notwithstanding their nutrition and health benefits, worldwide per capita consumption of fruit and vegetables is estimated to be 20-50% short of the minimum FAO and WHO recommended intake of 400 g/capita/day (FAO 2018). Sub-Saharan Africa and South Asia are of particular concern, with average consumption levels of only 206 g/capita/day of fruit and vegetables (Mason-D'Croz et al. 2019).

Vegetables provide promising economic opportunities for smallholder farmers as well as the basis for a healthy diet for all (Schreinemachers et al. 2018). Despite of this potential, low productivity in certain regions is still a serious obstacle. Average vegetable yields across sub-Saharan Africa, Southeast Asia and South Asia are estimated to be only 36%, 48% and 64%, respectively, of East Asia (FAOSTAT 2020), resulting in short supply of nutrient-rich vegetables. A variety of technological and socioeconomic factors are responsible for the low productivity and availability of vegetables as well as their value chain development in these regions. This precarious situation is further aggravated by climate change through increasing temperatures, changing precipitation patterns, and greater frequency of extreme weather events (IPCC 2019). A recent study of global vegetable and legume production concluded that if greenhouse gas (GHG) emissions continue on their current trajectory, vegetable yields could fall by 35% by 2100 due to high temperature, water scarcity and increased salinity and ozone (Scheelbeek et al. 2018). To alter this dire trajectory, there is an urgent need to strengthen the adaptive capacity of the vegetable value chain.

For the past five decades, the World Vegetable Center (WorldVeg) has conducted research to improve vegetable varieties and production systems that are adapted to the high temperatures and weather extremes in the tropical and sub-tropical regions with significant achievements and impact. By leveraging these achievements, WorldVeg is well positioned to expand its research portfolio to develop climate change adaptation and mitigation options along the vegetable value chain. These options should sustain or ideally enhance vegetable productivity and quality when averaged over a number of growing seasons despite climate change, reduce inter-season variability due to weather extremes, and limit post-harvest losses. In this paper, first risks of the vegetable value chain stakeholders to climate change are described. Next, the likely effects of climate change on vegetable productivity, and its subsequent effects along the vegetable value chain are discussed. This is followed by a description of mutually re-enforcing strategies that can be adopted by WorldVeg and partners to build climate resilience along the vegetable value chain.

2. Risks of Vegetable Value Chain Actors to Climate Change

Climate change will affect various groups of vegetable value-chain stakeholders more than others. The large differences in vulnerability seem to be a function of an individual stakeholder's position along the vegetable value chain (which, to some extent, determines their degree of exposure to climate-related effects), compounded by wider societal, cultural, horticultural and economic factors, such as gender, old-aged farmers, poor farming practices, limited access to climate-smart seeds and climate-smart technologies, and disparities in wealth. Vegetable farmers in low- and middle-income countries are among the vegetable value-chain stakeholders who are most vulnerable to climate-related effects given the nature of their farming systems and the socioeconomic landscape in which they operate. The bulk of vegetable farmers in the low- and middle-income countries operate on small (sometimes fragmented) farm holdings and cropping systems that are normally labor intensive and rain-fed. Additionally, many of these vegetable farmers operate with limited access to extension support services and financial assistance. As the climate becomes less predictable, these vulnerabilities are going to become more pronounced. Other value-chain stakeholders, such as packers, shippers, jobbers, agro-processors, wholesalers and retailers, are also vulnerable. In general, any disruption caused by climate change in local vegetable production will result in the loss of income for vegetable farmers and other vegetable value-chain stakeholders, and lead to an increase in vegetable price fluctuation in the domestic markets, which poses a threat to regional nutrition security.

3. Detrimental Impacts of Climate Change

Beyond the direct effects on weather elements, climate change will increase both abiotic stresses, such as elevated temperature, and biotic stresses, such as diseases and pests, on the vegetable value chain. Of great concern and largely unknown are the influences that interactions among different types of stresses may have on vegetable crops.

3.1. Abiotic stresses on vegetable crops

Carbon dioxide (CO_2). Carbon dioxide is fundamental to crop carbohydrate production, which is essential for crop growth and yield. Rising CO_2 levels will likely boost the overall productivity of vegetable crops (Bisbis et al. 2018), but any gains in yield may be offset partly or entirely by losses caused by other abiotic stresses, plant pathogens, phytophagous insects and weeds. Furthermore, given that CO_2 concentration increases, temperature and water availability will also likely change, which complicates making accurate predictions about vegetable production under elevated concentrations of CO_2. Daymond et al. (1997) reported that CO_2 enrichment alone increased onion bulb yields. However, on the other hand, Shaw et al. (2002) showed that elevated atmospheric CO_2 reduced plant growth when it was combined with other likely consequences of climate change, namely, higher temperatures, increased precipitation or increased nitrogen deposits in the soil.

Elevated temperatures. Air temperature is a predominant environmental factor for vegetable growth and yield. Vegetable crops have specific temperature requirements. They can be loosely grouped according to temperature requirement, such as hot season (e.g. amaranth, bitter gourd, mungbean, okra and sweet potato) with range of 18-35°C; warm season (e.g. eggplant, Capsicum species, pumpkin and tomato) with range of 12-35°C; cool-hot season (e.g. garlic, onion and shallot) with range of 10-30°C; and cool-warm season (e.g. brassicas, radish, etc.) with range of 7-25°C (Krug 1991; Lin et al. 2009). Temperature events higher than normal growth ranges are expected to influence growth and development that dictate potential yields and quality of vegetable crops. Nevertheless, vegetable crop response to elevated temperatures is not only species or variety specific, but depends also on growth stage and plant age. In general, temperatures higher than 35°C are known to inhibit seed germination and seedling emergence, disrupt normal photosynthetic processes and increase night-time respiration resulting in reduced biomass production for plant growth and yield. Moreover, high temperatures restrain organ modification for edible parts such as leafy head, bulb, tuber, fleshy stem, fleshy root, and curd, and disturb normal reproductive processes that lead to reduced flowering of cruciferous vegetables, and fruit and seed set of annual crops such as cucurbitous, leguminous and solanaceous vegetables (Wheeler et al. 2000). Elevated temperatures can also reduce postharvest quality of vegetable produces (Wheeler et al. 1998). Under high insolation and high humidity conditions harvested organ temperatures 8-10°C above that of ambient temperatures have been observed. In such conditions, harvested produce of field-grown vegetables often end up with undesirable quality such as blotchy ripening, sunburn, sun scald, etc. For all these reasons, adapting vegetable crops and cropping systems to temperature regimes will require region-specific crop adaptation strategies. On the other hand, in view of the predicted global warming, understanding the molecular basis of the relevant horticultural traits of priority vegetables is essential to allow breeders to design new ideotypes *in silico*, and ultimately develop new varieties for a wide range of heat stress conditions.

Extreme weather events. When the atmospheric CO_2 rises, the Earth not only heats up, but extreme weather events, such as lengthy droughts, untimely rains, heavy rainfalls and violent storms, may become more frequent. Untimely rains delay plantings and harvesting, and rains prior to harvest can cause cracking and splitting of vegetables of curd, head and fruit types, and pre-harvest sprouting of leguminous seeds, which lower not only yields but also produce quality. Torrential rainfall not only causes greater soil erosion and decreased soil quality, but also physically damages plant parts. It also attributes to high incidences of diseases and insect pests, reduced pesticide efficiency, physiological diseases, reduced fertilizer efficiency due to leaching of nutrients and reduced worker efficiency. Moreover, storms associated with torrential rainfall likely will wreak havoc across the whole vegetable value chain.

Waterlogging. Heavy rainfalls and faulty irrigation may result in waterlogging in soils with poor drainage. Waterlogging leads to low oxygen content and low rates of gas exchange in the soil, thus restricting respiration of the growing roots – all of which can damage vegetable crops (Patel et al. 2014). Plant age, time and duration of waterlogging, ambient temperature, condition of the floodwater and site characteristics influence significantly waterlogging sensitivity or tolerance among vegetable species, genotypes and rootstocks. Waterlogging coupled with elevated temperatures causes rapid wilting and death of herbaceous vegetables. Most global vegetables, especially those with shallow root systems, are sensitive to waterlogging resulting in dramatic yield losses, and genetic variation with respect to this character is rather limited. Exceptions are some regional traditional vegetables such as kangkong, Malabar spinach, jute mallow, water dropwort, etc. which are either semiaquatic or aquatic plants with lacunae gas spaces (aerenchyma) in the root cortex. In areas where waterlogging is expected to increase as a result of climate change, waterlogging tolerant vegetable crops such as traditional and indigenous vegetables may be a viable adaptation option besides improved management practices to overcome waterlogging damage. On the other hand, the utilization of waterlogging tolerant wild relatives of the vegetable crop of interest might enhance the chance of finding useful tolerance traits to be employed in breeding for waterlogging tolerance (Mustroph 2018).

Drought. The scarcity of rainfall without supplementary irrigation for a longer period of time leads to moisture depletion in soil, which causes drought stress in plants. The prominent effects on vegetable crops are reduced germination, decreased turgor, diminished net photosynthesis, lessened nutrient uptake, and stunted growth, thereby leading to a reduction in vegetable yield. Drought stress is often accompanied by elevated temperatures, which promote evapotranspiration and affect photosynthetic kinetics, thus intensifying the consequences of drought and further reducing vegetable yield. Vegetable crops being succulent (with water content more than 85% in edible parts except dry legume seeds) are susceptible to drought stress, particularly during formation of edible parts such as bulb, leafy head, tuber and curd, and flowering to seed development stages (Nakanwagi et al. 2020). As for succulent leafy vegetables, drought conditions reduce their water content and thereby diminish their quality. The adaptive mechanisms by which plants survive drought, collectively referred to drought tolerance, can be grouped into three categories: 1) a plant completes its life cycle before the onset of drought (drought escape);

2) a plant maintains its turgidity by increasing water uptake and reducing its transpiration despite drought (drought avoidance); and 3) a plant increases its water use efficiency of limited available water (dehydration tolerance). However, vegetable crops usually make use of more than one mechanism at a time to tolerate drought involving certain morphological, physiological and biochemical traits (Nemeskéri and Helyes 2019). Because of the complex nature of drought tolerance, developing global vegetables for drought tolerance is challenging but achievable by exploiting some of wild relatives with deep and extensive root systems (Wasaya et al., 2018; Karthika and Maheswari 2019). On the other hand, to produce vegetables during periods of water scarcity, there is a need for the development of cropping systems that entail selection of vegetables having a reduced water requirement, use of water conserving cultural practices, and adoption of water saving irrigation schemes.

Salinity. Under climate change scenarios, soil salinity increases in arid areas due to higher rates of evapotranspiration of shallow groundwater, and in coastal areas due to saltwater intrusion. Excessive soil salinity reduces the productivity of many vegetable crops, which are particularly sensitive throughout the ontogeny of the plant. The salinity threshold of the majority of global vegetable crops is low (sensitive to electrical conductivity units ranging from 1 to 2.8 deciSiemens per meter, dS/m, in saturated soil extracts) (Machado and Serralheiro 2017); however, there are species differences. For example, onions are susceptible to saline soils, while cucumber, eggplant, pepper and tomato are moderately sensitive to saline soils. Soil salinity can be accentuated by excessive use of groundwater, increasing use of low-quality water in irrigation, and overuse of chemical fertilizers. Thus, fertilization and irrigation management strategies must consider the effect of salinity on vegetable growth, crop salt tolerance, soil proprieties, and effects on water use efficiency and soil salinity. Drip irrigation and subsurface drip irrigation, compared with other irrigation systems, increase water use efficiency and create suitable root-zone salinity. While the use of brackish and saline water could help alleviate the drought problems, this option is only possible with the selection of salt-tolerant vegetables or management practices that alleviate salt stress.

3.2. Biotic stresses on vegetable crops

Changes in temperature, moisture levels and GHG concentrations because of climate change can stimulate the growth and generation rates of weeds, pathogens and their vectors, and insect pests, altering the interactions between weeds, pathogens, insect pests, their natural enemies, their hosts and their competitors. Thus, they create new ecological niches for the emergence or re-emergence and spread of certain plant diseases, insect pests and weeds. The effects could be felt in a number of ways, such as an increase in the frequency of outbreaks and the expansion of plant diseases, insect pests and weeds into new environments, as well as the evolution of new and more aggressive pathogen and pest strains and types, and increased vulnerability of plant defense mechanisms of usually tolerant or resistant vegetable crop varieties. Besides, with increasing globalization, the movement of planting materials by trade and travelers can be vehicles for the long-distance transmission of emerging/invasive plant pathogens, insect pests and weeds, which, in some cases, can result in total crop failure.

Plant pathogens. Plant diseases caused by bacteria, fungi, viruses and nematodes can be highly influenced by climate change (Nopsa et al. 2014). They tend to respond to climate change, through a number of interactions taking place among hosts, pathogen, and potential vectors. Elevated CO_2 may increase canopy density resulting in a decrease in light penetration, air circulation, and an increase in relative humidity, which encourage the proliferation, survival and dispersal of many fungal pathogens (Pannga et al. 2013). Frequent heavy rainfall can also influence the spread of plant pathogens, particular of many foliar diseases, such as anthracnose caused by *Colletotrichum* spp. (Ebert 2017), because many plant pathogens prefer humid conditions (Choudhary et al. 2018). High temperatures and moist soil generally favor the bacterial wilt pathogen, *Ralstonia solanacearum* (Namisy et al. 2019), and root-knot nematode, *Meloidogyne incognita* (Kim et al. 2017). High temperatures also favor the aggressiveness of the late blight pathogen, *Phytophthora capsici*, in pepper (Ebert 2017). Moreover, flooding can make the spread of water-borne pathogens easier.

Insect pests. Climate change exerts major changes in growth rate, development, number of generations, diversity, distribution, population dynamics and biotypes of insect pests, herbivore-plant interactions and infestation pressure (Juroszek and Tiedemann 2013). Virus-vectored aphids reproduce rapidly, and larval food consumption of fruit borer, *Helicoverpa armigera*, increases at elevated CO_2 levels (Akbar et al. 2017; Rao et al. 2016). High temperatures also speed up the growth and development rate of insects (Van Dyck et al. 2014), for example, shortening the larval developmental time of tomato pinworm, *Tuta absoluta* (Satishchandra et al. 2018). The higher the developmental rate, the more insect cycles per season and the higher the population size, resulting in more severe damage to vegetable crops. Along with indirect effects on natural enemies, competitors, parasitoids, and insect pathogens, climate change reduces the efficacy of pest control strategies (host plant defense and resistance, biological control, synthetic pesticides, etc.), increases the pesticide resistance of insect pests, and disrupts the synchronization in the prey-predation system, leading to a vicious cycle of increasing use of pesticides use that cause an increase in carbon footprint.

Pollinating insects. Honey bees, solitary bees, bumble bees, stingless bees and blow flies are major pollinators of brassicas, Capsicum peppers, cucurbits, eggplant, legumes, okra, onion, etc. These minute creatures ultimately decide the fruit yield, seed production and produce quality through their pollination services. However, climate change may cause a mismatch of flowering time of vegetable crops and emergence of their pollinators affecting not only pollination but also pollinators' health due to limited nectar and pollen sources. Higher temperatures are also increasing incidences of pathogens and parasites of pollinators that shrink their populations (Soroye et al. 2020). This is further exacerbated by the increased use of pesticides due to climate change (Cariveau and Winfree 2015).

Weeds. Climate change is expected to bring about a shift in the floral composition of cultivated vegetable crop stands – with weed species distribution and their competitiveness altering. Weeds are highly adaptable adverse environmental conditions and hence any factor which increases abiotic stresses on vegetable crops may render them less competitive with weeds. Increases in atmospheric CO_2, rainfall and temperature affect existing plants (weeds shift) and allow some other plants (weeds) to replace native ones and expand in to new areas, where they did not exist before (Amare 2016; Karkanis et al. 2018). Increase of root or rhizome growth of perennial weeds (e.g. *Cyperus* spp., *Digitaria* spp. etc.) may make it harder to control them as they easily regrow from root fragments left after tillage. Even under drought conditions, some weeds produce allelochemicals that make them thrive well and compete with cultivated vegetable crops. Because of the physiological plasticity of weeds and their intraspecific variation, controlling weeds under climate change scenario is likely to be challenging. Thus, extensive research and evaluation of appropriate herbicides and bio-control agents will be required. Adoption of ecological approaches (e.g. selection of suitable vegetable crop species and varieties, intensive cropping systems, and improved soil management) may also enable to reduce weed problems.

3.3. Postharvest losses and waste

Vegetables are very sensitive to damage after harvest and are more perishable than cereal grains or tuber crops. Post-harvest losses and waste in the vegetable value chain are large, estimated from 30% to 40% in low-income countries (Bhattarai 2018). Postharvest losses and waste can occur at every point along the vegetable value chain, including during storage, whether on-farm or at the market; transport from farm to processing factories or markets; vegetable produce discarded in processing factories; vegetable produce not sold in shops or restaurants; kitchen scraps; and plate waste. Such losses and waste not only decrease the amount of available vegetables, which raises prices but also increase GHG emissions. Postharvest losses and waste also squander the resources used to produce the lost vegetable food in the first place (e.g. fertilizer, irrigation water and human labor). A number of causes of postharvest losses and waste are likely to be exacerbated by elevated temperatures, rainfall variability, and other extreme weather events.

3.4. Decreased nutritional value

While higher CO_2 levels can increase the amount of carbohydrates for plant growth, this comes at the expense of lowering nutritional quality in the edible part of vegetables (e.g. less protein, zinc, iron and magnesium) (Dong et al. 2018; Beach et al. 2019), which make vegetables less inherently nutritious and likely will slow the progress of the efforts in decreasing global nutrient deficiencies. The effects of lowering nutritional quality may be due to dilution by increased carbohydrate content, altered physiological requirements that change partitioning of nutrients among tissues, and decreased transpiration leading to reduced flow of nutrients. This suggests that increased emphasis on research evaluating nutrient composition of vegetable crops, as well as their yields, will be needed. On the contrary, abiotic stresses such as elevated atmospheric CO_2 concentrations, drought and salinity are elicitors of the biosynthesis of many metabolites in plants, including a wide range of bioactive compounds, which serve as functional molecules to cope with stressful conditions. The accumulation of bioactive compounds such as carotenoids, polyphenols, flavonoids, anthocyanins, and glucobrassicin with their active antioxidant activities offers nutraceutical values to vegetables and has potential human health benefits. In order to improve and exploit the nutraceutical properties of vegetable crops, controlled abiotic stresses, without affecting the yield, have been suggested (Sarker and Oba 2019; Toscano et al. 2019). This practice can also reduce water use and enhance usage of saline or sub-optimal cultivation environments.

3.5. Occupational hazards and food safety

While the impact of abiotic and biotic stresses on vegetable production and nutrition security are obvious, it is important to note that these factors may also have significant impact on the safety of vegetables and legumes. Weather variability and extreme events due to climate change will result in higher volumes of chemical pesticides that will have to be applied to control diseases and insect pests. This may result in high levels of the farmer's direct exposure to hazardous pesticides, and the consumer's exposure to pesticide residues on vegetable produces. Furthermore, a wide spectrum of human pathogens that have been reported to be adhered with vegetables (Klingbeil and Todd 2018) are closely linked with high temperature and humidity (Deuter 2014). High temperature and humidity also stimulate mold proliferation and accumulation of carcinogenic mycotoxins on grain legumes. Produced by fungi, mycotoxin contamination can occur in the field or after harvest when produce is improperly stored (Yeni et al. 2016).

4. WorldVeg's Prospects for Climate Resilient Pathways

The Earth's climate has always been in a flux, but the current rate of change and the range of weather variables are far beyond what previous generations of farmers and other agro-food stakeholders have had to face. Farmers, other value chain actors, and consumers are both at risk as is evident from what is described above. WorldVeg and partners can contribute to climate resilience at different nodes in the vegetable value chain, in particular as related to:

(i) Climate-smart seed
(ii) Climate-smart crop management practices and cropping systems
(iii) Climate-smart post-harvest practices and circularity
(iv) Mobilizing the private sector
(v) Mobilizing policy engagement

A mix of these approaches across space and time can help address immediate needs as well as building enabling conditions to assist smallholder farmers and other stakeholders in the vegetable value chain to respond to climate change challenges. The approaches are discussed in more detail below.

4.1 Climate-smart seed

WorldVeg has developed varieties of priority vegetables such as tomato, pepper, brassicas and mungbean with heat tolerance, disease resistance and drought avoidance. But with more severe and frequent challenges from aggravated climate change, additional immediate efforts capitalizing research findings of the past are required to overcome the challenges. This will require access to promising germplasm, quality information about germplasm materials, shortened breeding cycles, high selection intensity, wide-scale phenotyping, accurate selection supported by genomic technology, multi-location testing systems that adequately sample the target population of environments so as to deliver durable adaptation of incumbent and new vegetable crops in real time, and modeling approaches to aid ideotype design of future varieties and predict performance of specific genotypes in new environments.

Germplasm collection and conservation. Globalization has already induced a tendency towards uniformity in eating habits, which leads farmers to concentrate on fewer and fewer vegetable crop species. And climate change, a product of the very process of globalization, is also eroding crop genetic diversity faster than ever. To counter the increased likelihood of extinction for regionally adapted and consumed traditional (indigenous or endemic) vegetable species (whether cultivated or foraged), and to build the robust, climate-resilient and sustainable vegetable production capacity that enhance diet diversification to improve nutrition and health, there is an increased need for consolidating collection and conservation of vegetable germplasm, including both wild relatives of global vegetables and underutilized traditional vegetables.

Screening of WorldVeg genebank germplasm for identification of resistance/tolerance to abiotic and biotic stresses. The WorldVeg gene bank houses a large collection of germplasm, holding more than 60,000 accessions from more than 400 vegetable species. It is important to recognize that for WorldVeg the end product of germplasm collection is not conservation per se but the effective utilization of conserved germplasm. Thus, concerted efforts are needed to screen these valuable genetic resources, especially landraces and wild relatives of priority vegetables, for resistance/tolerance to high temperature, flooding, drought, prevailing and emerging diseases and insect pests, high nutrient content and health qualities. Continued work in this area, coupled with the use of physiological and horticultural traits and multiple molecular marker tools, will assist plant breeders in dealing with current abiotic stresses, and future disease and pest outbreaks, to develop "low input vegetable varieties" that minimize GHG emissions.

Traditional vegetables. Traditional (indigenous) vegetables will likely play a key role in climate-resilient vegetable value chains, despite the fact that they currently constitute a small share of agro-food systems (Keatinge et al. 2015). Many traditional vegetables are highly nutritious, containing several micronutrients plus nutraceuticals. Their suitability to marginal niche and low-input environments offers opportunities for low GHG emissions from an agro-ecosystems, production, and processing perspective, as well as the adaptive capacity of most agro-food systems. Traditional vegetables also represent a broad gene pool for future vegetable crop improvement. To mainstream underutilized traditional vegetables as new vegetable crops, concerted efforts in research and development need to focus on: 1) screening of traditional vegetable germplasm conserved in WorldVeg's genebanks for market potential, in particular taste, nutrient and anti-nutrient contents, health compounds for fresh, processed food or as ingredients; 2) screening of the same for desirable horticultural traits and resistance/tolerance to abiotic and biotic stresses; 3) eco-physiology and production practices of selected traditional vegetables; 4) postharvest management system to prolong shelf life; 5) preparation methods to ensure nutrient availability, remove anti-nutrient factors and enhance attraction and taste; and 6) seed production and seed systems (formal and informal).

Genomics-assisted breeding. Phenotypic selection in conventional breeding programs of WorldVeg's priority global and traditional vegetables to combine desirable traits in a step-wise manner is both laborious and time consuming, particularly for complex traits with polygenic control and under high environmental variation. The resulting time frame can be 10-15 years before the promising varieties can be released. Recent advances in genomics-assisted breeding methods using next generation sequencing (NGS) technologies have been able to identify adapted traits represented by genes or groups of genes that contribute to resistance/tolerance to abiotic and biotic stresses at an ever-reducing cost (Poland and Rife 2012; Manivannan et al. 2018). By employing NGS technologies, WorldVeg breeders can more rapidly introgress desirable genes from landraces and wild relatives of priority vegetables, and identify breeding lines with enhanced productivity even in the presence of drought, heat, waterlogging, and disease and pest pressures relative to the current varieties available. As the cost of genome sequencing drops, researchers will also be able to apply these technologies on germplasm collections and breeding populations. This will allow them to uncover the genomic basis of resistance/tolerance to abiotic and biotic stresses in vegetable crops, and identify locations on the genome where breeders have most successfully selected and bred for adaptive traits in the past, providing additional knowledge to improve vegetable yield. Moreover, genome-wide prediction (also known as genomic selection) and breeding simulations are helping breeders make better selections in their programs because they can improve their prediction of the outcome of breeding decisions using forward breeding.

High throughput phenotyping. Recent advances in field-based high-throughput phenotyping platforms render non-destructive screening of larger number of samples with higher accuracy and reduced costs for different categories of traits possible, and provide a high capacity for data recording, processing and interpretation together with automated environmental data collection (Chawade et al. 2019). The obtained phenotyping data processed through an open-source data management system such as Phenotyping Hybrid Information System (PHIS) are potentially useful to unlock the genetic potential and improve prediction of complex traits, like yield and resistance/tolerance to abiotic and biotic stresses, which are characterized by strong environmental context dependencies, i.*e.,* genotype by environment interactions. Integrating whole plant phenotyping data with genotyping data (D'Agostino and Tripodi 2017), will lead to the identification of alleles associated with target traits and accessions that can be used as parents for breeding programs, and aid the pyramiding of desirable genes appropriate for specific environments at a faster pace.

Coordinated field-level evaluation. Breeding programs for resistance/tolerance to abiotic and biotic stresses of WorldVeg's priority global vegetables rely on the detailed observation of advanced pedigree lines across different production environments. The effort will be greatly enhanced by the development of data standards and intercomparable data, related to yield performance and stability, to be employed by WorldVeg scientists and partners in different regions. This should include protocols for standardized data collection and calibration, gold standard datasets for algorithm validation and annotation, and common data exchange formats for interoperability among partners. The protocols could also be applied for the selection of desirable traditional vegetables to identify promising traditional vegetables for specific regions.

Open seed systems. Climate-resilient vegetable seeds are a prerequisite to building climate-resilient vegetable value chains because all value chain stakeholders are dependent on the quantity and quality of climate-smart seeds among other factors. To increase smallholder farmers' access to a diversity of WorldVeg's improved vegetable varieties that will arm them with options to better manage abiotic and biotic stresses incurred by climate change, WorldVeg is to distribute its improved materials in accordance with the International Treaty for Plant Genetic Resources for Food and Agriculture. To accelerate development and dissemination of climate-resilient vegetable varieties, WorldVeg will strengthen its partnerships with national agricultural research systems where these play an important role in seed systems (e.g. for legumes like mungbean), and private seed companies (members of the WorldVeg convened consortia in Asia and Africa) through their extension and marketing channels. WorldVeg will also work through the informal seed sector to promote distribution of quality seed for traditional vegetables that are not (yet) targeted by the formal seed sector.

4.2 Climate smart crop management practices and cropping systems

Crop diversification coupled with appropriate crop management practices and cropping systems decreases the risks of climate change and livelihood insecurities, but can also be a way to increase wealth when producing high-value vegetables. Since not all targeted regions are predicted to experience the same vulnerabilities to climate change, adaptation and mitigation strategies will vary. Therefore, appropriate, site-specific crop management practices, pest management systems and cropping systems need to be developed so as to alleviate the effects of abiotic and biotic stresses. Other technologies and management tools that can accelerate the adaptation of vegetable cropping systems include protected cultivation, drip irrigation and hydroponics, simulation modeling and remote sensing. These technologies, combined with location-specific information, will help to maximize productivity under climate change conditions.

Multifunctional cropping systems. The principle takes advantage of favorable growing conditions to offset negative impacts of climate change. They include: 1) matching environmental requirements of specific vegetable species and varieties with spatial and temporal environmental variability to escape or avoid abiotic and biotic stresses; 2) integrated crop and soil management and biocontrol-based integrated pest management to escape, avoid or attenuate abiotic and biotic stresses, and improve soil fertility; and 3) multiple cropping of different vegetable species and varieties in intercropping, mixed cropping, relay cropping, sequential cropping or multi-story cropping to grow nutrient-rich vegetable crops, reduce the incidence of diseases and pests, increase nutrient and water use efficiency, enhance climate resilience (e.g. intercropping with legumes to reduce nitrous oxide emission), and produce vegetables almost year-round to improve household nutrition. In addition to support climate-resilient vegetable production, multiple cropping systems with diverse vegetable types generally enhance dietary diversity, which typically reflects a higher quality diet more likely to meet consumers' nutrient needs.

Climate-smart pest management (CSPM). Changes in temperature and rainfall can contribute to the faster evolution of new and more aggressive strains and types of pests (i.e. plant pathogens, insects, mites and weeds). To promptly contain the spread of these emerging and invasive pests, rapid identification and monitoring—for instance through drones and other remote sensing techniques— of pests and surveillance of emerging threats are imperative. The collected data are then applied to build crop/weather/pest interactive models that can be used as a confidence measure for threshold-based decisions for CSPM, which considers adaptation and mitigation strategies simultaneously wherever possible. Proactive measures of primarily non-chemical preventative approaches that include the use of disease-free seeds of pest resistant/tolerant varieties; crop sanitation; crop rotation; altering planting dates; grafting with disease-resistant stocks; release of biological control agents (e.g. antagonistic microorganisms, predators, parasitoids, insect pathogens, botanicals and competitors), pheromones and allomones; planting of trap crops; soil solarization; mulching; tillage; etc. are then developed and put in place. Whenever proactive measures have not been adequately effective, reduced-risk pesticides are identified and used as a last resort, and with care to minimize risks.

Improved decision-making through crop modeling. Crop models integrate important information about genotype of vegetable species/variety, environment, management and socioeconomic status to understand their interactions. They can be employed to predict the expected yield for deciding agronomic practices and cropping systems (including selection of vegetable species/variety, planting date, and optimization of planting dates, and irrigation and fertilization schedules) for different regions, as well as to better understand the potential impacts of climate change on crop productivity (Asseng et al. 2015) so as to minimize the risks and increase nutrition security. In addition, the use of genomic selection and crop models linked to environmental data can help make breeding decisions so as to reduce the time required to develop new varieties.

Improved decision-making based on crop and field monitoring. Monitoring of weather patterns, soil conditions, abiotic and biotic stresses in field conditions, and crop growth and yield is essential for profitable vegetable production. By integrating datasets from field-based sensors or using remote sensing, strategies can be devised to deploy suitable vegetable species/varieties and designing appropriate crop management practices that offer the best chance for a productive harvest under current and climate change conditions. Concurrently, advancements in internet and communication technologies increase the usability of information derived from monitoring, which may enable smallholder vegetable farmers to apply precision agriculture at scale and farm more efficiently, profitably, and sustainably.

Precision agriculture. Precision agriculture technologies facilitate the employment of integrated crop management to sow the right seeds, and apply right fertilizers, water and pesticides, in the right amount, in the right place, and at the right time for the purpose of increasing productivity and economic returns, while reducing GHG emissions, waste and contamination of soil and water bodies due to runoff from the fields (Balafoutis et al. 2017). Precision agriculture is based on the application of information technology to a description of variability in the field, variable-rate operations and the decision-making system, involving remote sensing, weather-tracking technology, proximal data collection and computer-based applications. Precision agriculture technologies are being employed in large-scale, industrial farming in high-income countries. Although the promise of precision agriculture holds true for vegetable crops, the future direction for WorldVeg and its private and public partners are to develop site-specific precision agriculture technologies and strategies for small-scale vegetable fields in low- and middle income countries, which should be economically viable and easy for smallholder farmers to adopt.

Protected cultivation. To cope with extreme weather elements, protected cultivation, wherein the microclimate surrounding the plant body is controlled, is one of the options. It allows: 1) producing vegetables in areas where field production is challenging due to extreme weather conditions; 2) controlling diseases and insect pests with minimal pesticide application; 3) using water and fertilizers efficiently; 4) intensification aiming for higher productivity levels because of reduced risk; 5) prolonging the harvest period. High quality vegetable produced in protected cultivation enhance smallholder farmers' access to higher off-season prices. Low-tech protected cultivation techniques such as rain shelter, high or low tunnel, netting, screen-house, etc. may be employed in low- and medium-income countries for adapting to climate change; however, they have to be combined with other methods to ensure adequate pest control (Nordey et al. 2017). Even so, plastics as covering materials after their use need to be cleaned and separated for reusing or recycling.

Drip irrigation and hydroponics. With climate change, water supplies are expected to become threatened. Nevertheless, water management strategies, such as drip irrigation, can conserve water and protect vulnerable vegetable crops from water shortages. Drip irrigation reduces demand for water and reduces water evaporation losses by providing the necessary water resources direct to the vegetable crop when required. Through improved drip irrigation methods based on real-time crop need, better understanding of plant nutrition and improved vegetable varieties, better drought and heat avoidance in vegetable crops grown in rain-fed conditions can be obtained. Besides, hydroponic techniques such as nutrient film technique, ebb and flow technique, and wick technique greatly conserve water because the same water can be reused over and over. As most of these hydroponic techniques are operated under protected conditions, vegetables can be produced all year round.

4.3 Climate-smart postharvest practices and circularity

Measures to reduce postharvest loss and waste from the vegetable value chain can decrease the carbon footprint and increase climate resilience. Globally, about one third of food is wasted, which accounts for about 8% of global carbon footprint. In this carbon footprint of total food waste, vegetables contribute 22% (FAO 2015). Nonetheless, reducing postharvest losses and waste requires reliable data on where, when, why and to what extent they are occurring, especially for smallholder production and its milieu, in order to determine the best intervention options to meet the needs.

Postharvest system. Actions are needed for protecting nutrients in the vegetable value chain and increasing resilience to climate change beyond vegetable crop productivity. This requires a focus to reduce the costs and economic viability of innovations in packaging and storage (longer shelf-life and reduced perishability through cooling or refrigeration), processing (aimed at retaining nutrients and quality of produces and ensuring safety), lowering GHG emissions associated with value-chain activities wherever possible, and marketing. Engagement with the private sector is also necessary to enable a successful promotion of efficient energy use in vegetable food processing and packaging, and campaigns to encourage less consumer food waste.

Circular agriculture. Circular agriculture represents the opportunity to turn the whole vegetable value chain from a contributor to climate change to an actor in the solution. This includes re-using and re-purposing of on-farm crop residues and culled produces because of minor blemishes, postharvest losses, discards from supermarkets and processing facilities, and consumption waste avoiding GHG emissions. They may include processing fresh culls for other uses (e.g. vegetable juice, dehydrated and powdered vegetables, and fermented vegetables), composting crop residues and waste, and converting on-farm biomass into biochar or using them as mulching materials. The effect of compost and biochar is to improve the soil's physical structure and nurture beneficial microbes and mulch to suppress weeds, leading to a cascade of system benefits not only carbon sequestration, but also better water retention and reduced reliance on synthetic fertilizers.

4.4 Weaving urban agriculture into nutrition security and resilience

Urban and peri-urban agriculture is credited with providing a series of benefits, such as reducing food carbon footprint by producing fresh vegetables close to urban markets; reducing fertilizer use and energy consumption by productive re-use of urban organic waste (De Zeeuw et al. 2011). An example from urban areas is the production of perishable leafy vegetables that cannot be stored for a long time and depend on short transportation distances. In this context, urban and peri-urban agriculture may contribute to nourish the urban poor and vulnerable groups in case supply lines of nutritious and healthy food are compromised by major disasters such as floods, storms or water scarcity caused by climate change. However, this only could be achieved with availability of climate-smart vegetable seeds and improved production technology packages. Additionally, soil-based cultivation of vegetables in the urban and peri-urban areas helps to prevent soil degradation and surface run-off, as well as to reduce the urban heat island effect through increased evapotranspiration.

4.5 Mobilizing humanitarian partners

People are trying to adapt to the changing environment, but an annual average of 21 million people in sub-Saharan Africa, Southeast Asia and Latin America have been forcibly displaced by weather-related sudden onset hazards – such as floods, storms, wildfires, extreme temperature –each year since 2008 (UNHCR 2019). When natural hazards destroy food production systems that impact on the nutritional status of affected populations, vegetables can help rebuild local food supplies and provide nutrition for survivors. Towards this direction, WorldVeg has distributed more than 65,000 disaster seed kits through humanitarian partners to the victims of major disasters in Africa and Asia since 2000. The kits include seed of locally adapted varieties of nutrient-rich, fast-growing vegetables, and technical information in local languages on vegetable production, food preparation and preservation methods. With continuing support from the donors and humanitarian partners, WorldVeg will strengthen this service.

4.6 Mobilizing the private sector

To deliver climate-smart seed, crop management practices and cropping systems, and post-harvest practices and circularity at scale, there is a need for active dialogue and collaboration with the private sector. WorldVeg-private sector partnerships would facilitate the private sector investment decisions and support solutions to be scaled up along the entire vegetable value chain. The current strong partnership between WorldVeg and the seed sector in Asia and Africa can serve as an example. The private sector could ensure more informed decision making about seed choices, and provide an adequate and consistent supply of climate-resilient vegetable seeds. In addition, the private sector has particular competencies and knowledge that can make a unique contribution to climate change adaptation and mitigation for other stages of the vegetable value chain. There are several investment opportunities available to the private sector, including agricultural extension and marketing information via digital advisory services, drip irrigation, solar pumps, crop and soil monitoring, protected cultivation, postharvest technologies, processing, design of resilient infrastructure, etc. Yet, for the private sector to step up their efforts, the provision of short-term and long-term loans or direct supports from the governments and development organizations is essential. The private sector's contribution to a thriving and successful climate-resilient vegetable value chain will create jobs and provide economic and livelihood benefits.

4.7 Mobilizing policy engagement

Scaling up climate resilient pathways to trigger the desired transformation in the vegetable value chain must be incorporated, integrated or mainstreamed into the government policies and on-going development programs if these pathways are to be sustainable and applicable on a wide scale. This will require supportive financial mechanisms and instruments that create an enabling environment for adopting climate-resilient pathways at local, national and regional levels, and accommodate the different risk-return profile of each of the stakeholders involved. Given the shorter growing cycle and higher perishability of most vegetables due to weather shocks (e.g. heavy rain, flood, drought, etc.), social safety nets are required to make sure that climate-resilient initiatives conform to the principle of sustainability, at the production, economic and nutrition system levels. For the majority of smallholder vegetable farmers and small-sized enterprises in low- and middle-income countries, the microfinancing system that provides flexible unsecured loans would be desirable. For the large-scale commercial vegetable production and medium-sized enterprises, on the other hand, index-based crop insurance could be employed. In this paradigm, insurance payouts are pegged to well-defined weather risks and yield levels measured by remote-sensing technology and calculated by data analysis.

5. The Way Forward: A Call for Joint Action

WorldVeg recognizes that the multi-dimensional nature of the climate-resilient vegetable value chain (productivity, adaptation, mitigation, economic returns, safety and nutrition) make it challenging to develop the aforementioned pathways to climate resilience, which likely entail spanning spatial and temporal time scales in an iterative process. This ultimately will require political will of all stakeholders – be they WorldVeg, governmental decision-makers, national agricultural research systems, donors, other international agricultural research centers, private sector or academics – to engage in science-policy dialogs to facilitate establishing active collaboration and partnerships in the development of climate-resilient pathways and mainstream them into development plans. The science-policy dialogs will involve the ex-ante proactive assessment of different options to explicitly address the adverse impacts of climate change, and of the costs and benefits of actions that are relevant to all partners and stakeholders. Thenceforth, there will be the ex-post reflective assessment of evidence-based data showing the positive impacts of adopting best-bet climate-resilient technologies. Hopefully, these science-policy dialogs will also serve to improve advocacy efforts that are critical to securing sustainable funding to achieve desired outcomes and impacts, as well as to meet the Sustainable Development Goals.

6. Contributions to the Sustainable Development Goals (SDGs)

Climate-resilient vegetable value chain directly contributes to a number of SDGs: SDG 1 (No Poverty) and SDG 2 (Zero Hunger) through its direct impact on vegetable production, value addition and income generation; SDG 3 (Good Health and Well-being) through increased consumption of nutrient-rich vegetables; SDG 12 (Responsible Consumption and Production) through reduction of vegetable produce losses and wastage at the primary and secondary production stages; SDG 13 (Climate Action) through, among others, improving GHG efficiency per unit of vegetable output; SDG 15 (Life on Land) through conserving and utilizing diversity of indigenous and traditional vegetables; and SDG 17 (Partnerships to achieve the Goal) through a broad range of regional and in-country partnerships and by providing logistics and other services.

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WorldVeg Publication No.: 20-843