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Potato production in relation to climate change

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Abstract
Potatoes constitute the world's main non-cereal food crop, ranking fourth behind rice, wheat, and maize. Potato (Solanum Tuberlosaum) is a very sensitive crop species to both temperature and rainfall. It does well in temperate cool climates with the optimum temperatures of 18 ^{0}C and moderate rainfall that's ranges between 850 mm to 1200 mm in a growing season and at altitude between 1400m and 3000m above the sea level. Climatic factors directly influence crop potential productivities, regulating its transpiration, photosynthesis, and respiration processes in such a way as to control the growth and development of the plants throughout their physiological cycle. Climate change and variability is one of the biggest challenges that the agriculture sector is facing today as it is the main determinant of the crop production. Impacts of climate change might be positive or negative. It has been seen that global warming has brought about a decrease in production due to changes in annual and seasonal rainfall, more erratic weather patterns and more intense and frequent extreme weather events such as heat waves, drought, storms and floods .This indicates mixed impact on potato production implying uncertainty and therefore need more research in different spatial and temporal over the Earth surface. Therefore knowledge of climatic requirements of potato and its physiological responses to the environment is extremely important to help growers produce high yields with good tuber quality under different atmospheric conditions.

Keywords: Climate change, potato, yield, productivity

Introduction

The potato (*Solanum tuberosum* L.) is a member of the nightshade family (Solanaceae) and is a major world food crop and by far the most important vegetable crop in terms of quantities produced and consumed worldwide. Potato is exceeded only by wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and maize (*Zea mays* L.) in world production for human consumption (Bowen, 2003) [1, 22]. Potato tubers give an exceptionally high yield per acre and are used in a wide variety of table, processed, livestock feed, and industrial uses (Feustel, 1987; Talburt, 1987) [2, 5]. Potato provides nutritious food in a diversity of environments. Potato can be an important food for the increasing world population, and has the potential for increased vitamin C and protein content. The mainly limiting factors for potato production are heat and water stresses. The effects of these factors on physiology, yield and grade of potato crop are thoroughly discussed in the current contribution. The meteorological elements governing growth, development, production, and quality of potato tubers at a given site are basically air and soil temperatures, solar radiation, photoperiod, soil moisture, and crop water use or evapotranspiration. Potato originated from tropical areas of high altitude in the Andes.

Climate change has profound effects on agricultural productivity on a global scale. India is expected to be adversely affected by climate change and variability (Kumar *et al*., 2015) [3, 9]. Temperatures are projected to rise by 0.5 °C by 2030, resulting in fewer rainy days and more extreme weather events, such as prolonged droughts. If left unaddressed, climate change and variability may undermine rural incomes and food security in India by longer spells of water shortages and increased incidence of pest and diseases (Singh *et al*., 2013) [4]. Potatoes, in addition to cereals, contribute largely to food security in India. In 2016, potatoes in India occupied an area of 2.13 million hectares, total annual production reached almost 44 million tonnes and yields averaged 20.5 tonnes per hectare (Directorate of Economics and Statistics, 2017). With a projected population increase of 19% by 2050 (United Nations, 2017), India faces a tremendous challenge to increase production of all food crops, including potatoes, to meet future demands. Without adaptation to climate change and other mitigation to technological adaptation gaps, simulations project a 23% decline in potato yields by the years 2040–2059 (Hijmans, 2003) [7]. Other simulations are less severe, projecting a yield reduction of 'only' 2.5–13.72% between 2020 and 2050 (Singh *et al*, 2009; Kumar *et al*., 2015) [8, 24, 3, 9].

Due to India's size and agro-ecological diversity, climate change and variability affect India's states differently. For example, seasonal temperature increases beyond the optimum have negative effects on yields particularly in Central and Eastern India (Dua *et al*., 2013; Haris *et al*., 2014) [10, 11]. On the other hand, in the north-western parts of the country, yield gains are expected as temperatures move towards optimal levels from current low temperatures (Singh *et al*, 2009) [8, 24]. The temperate Indian hills are highly susceptible to severe epidemics of late blight, but the disease now appears earlier in the northern part (November) and later in the eastern part (February) and within a wider temperature range (Gautam *et al*., 2013) [12]. Adaptation to climate change is crucial for increasing yields or, at best, maintaining yields at current levels. Various strategies exist, such as shifting cultivation to cooler seasons, increasing fertilizer application to compensate for increased loss at higher temperatures (Kumar *et al*., 2015) [3, 9], mulching, or implementing water and soil management strategies and pest and disease management strategies (Singh *et al* 2009; Thomas-Sharma *et al*, 2016) [8, 24, 13]. The adoption of improved crop varieties is another important adaptation strategy. Using early-maturing varieties, which mature between 70 and 90 days, allows for more flexibility in planting or harvesting the crop and potentially provides additional income if cultivated in between two rice cycles (Bardhan Roy, *et al*., 2007) [14]. Other relevant varietal traits are resistances and tolerances to biotic and abiotic stresses, such as heat and drought tolerance (Islam *et al*., 2016). Take the example of heat stress, which poses a major threat to potato production, due to the delay in tuber initiation, malformation and necrosis of tubers (Levy and Veilleux, 2007) [15]. In addition, drought may affect potato production, not only by limiting the plant to absorb water, but also by increasing the salt concentration in the soil, which affects the reverse osmosis of water loss from plant cells (Basu *et al*., 2016) [16]. Furthermore, late blight and virus resistance will become increasingly important traits as diseases evolve (Chowdappa *et al*., 2015) [17] and pests and pathogens spread more freely (Bebber *et al*., 2014) [18].

The aboveground stems of potato plants are erect in early stages of development but later become spreading and prostrate or semi-prostrate. The tuber is an enlarged underground stem. The tubers have buds or eyes, from which sprouts arise under certain conditions. Tubers are harvested for both food and seed. The flowers and fruits are only important to potato breeders. Potato has a relatively shallow, fibrous root system with the majority of the roots in the surface 0.3 m (Lesczynski and Tanner, 1976; Tanner *et al*. 1982) [19, 20]. The root system develops rapidly during early growth and achieves maximum development by mid season. Thereafter, root length, density, and root mass decrease as the plant matures. Rooting depths of 1.2 m or more have been reported for potato under favorable soil conditions (Durrant *et al*. 1973) [21, 112]. Potato extracted less water from the soil than barley (Hordeum vulgare L.) and sugarbeet (Beta vulgaris L.) and the differences were accentuated below 0.6 m depth (Durrant *et al*. 1973) [21, 112]. The origin of potato in cool climates with equatorial day lengths, and the shallow potato root systems have consequences for the agrometeorological responses of the crop. Knowledge of climatic requirements of potato and its physiological responses to the environment is extremely important to help growers produce high yields with good tuber quality under site-specific atmospheric conditions. Crop weather models can be used to provide estimates of potato yield as a function of climatic factors at a particular locality. The SUBSTOR-Potato model, for instance, takes into consideration daily data of temperature, photoperiod, intercepted solar radiation, soil water and nitrogen supply. The model simulated fresh tuber yields ranging from 4 Mg ha-1 to 56 Mg ha-1 due to differences in climate, soils, cultivars and management practices (Bowen, 2003) [1, 22]. According to the Agriculture, Food and Rural Development Department (2005), potato plant has five growth stages: sprout development (I), plant establishment (II), tuber initiation (III), tuber bulking (IV), and tuber maturation (V). Timing and duration of these growth stages depend upon environmental factors, such as elevation and temperature, soil, moisture availability, cultivar and geographic location.

At growth stage I, sprouts develop from eyes on seed tubers and grow upward to emerge from the soil, roots begin to develop at the base of emerging sprouts, and the seed piece is the sole energy source for growth during this stage. At stage II, leaves and branches develop on emerged sprouts; roots and stolons develop below ground, and photosynthesis begins. Potato development in stages I and II lasts from 30 to 70 days,depending on planting date, physiological age of the seed tubers, cultivar, soil temperature, and other environmental factors. At stage III, tubers form at stolon tips but are not yet appreciably enlarged and in most cultivars the end of this stage coincides with early flowering with an average duration of roughly two weeks. At stage IV, tuber cells expand with the accumulation of water, nutrients, and carbohydrates. During tuber bulking stage, tubers become the dominant site for carbohydrate and inorganic nutrient storage. Tuber bulking can continue up to three months as a function of the cultivar and environmental conditions. During stage V photosynthesis gradually decreases, leaves turn yellow, tuber growth rate slows, and the vines die. Maturation may not occur in the field when a long season variety like Russet Burbank is grown in a short season production area.

Agroclimatology of the crop

Kooman *et al*. (1996) [23] reports three phenological phases in the allocation of daily accumulated dry matter. Initially, dry matter is divided between stems and leaves (growth stage II). In the second phase, which starts at tuber initiation, an increasing amount of accumulated dry matter is allocated to the tubers and a decreasing fraction to the leaves (growth stages III and IV). In the third phase all assimilates are allocated to the tubers (growth stage V). Leaf growth stops and photosynthesis eventually stops because of leaf senescence. Climatic factors influence all three phenological phases. The duration of the first phase, comprising the development period between emergence and tuber initiation, is shortened by short days and temperatures less than 20 ºC. Tuber initiation is slower at temperatures over 20 ºC. The duration of the second phase is affected by temperature with an optimum between 16 and 18 ºC (Van Heemst, 1986) [24] or 14 and 22ºC (Ingram and McCloud, 1984) [25] and by solar radiation. Crop senescence is shortened by high temperatures, especially greater than 30 ºC (Midmore, 1990) [26]. The effects of agroclimatological factors on physiological parameters of potato, especially on tuber yield, grade, and internal quality, will be discussed below.

Air Temperature, Solar Radiation and Photoperiod

Due to the interactive effects of air temperature, photoperiod (day-length), solar radiation, and cultivar on the tuberization stimulus, these meteorological variables will be discussed together with emphasis on physiological responses to one or another climatic element consistent with the specific objectives of each research project. The review by Haverkort (1990) [27] points out that potato is best adapted to cool climates such as tropical highlands with mean daily temperatures between 15 and 18ºC as encountered in its center of origin. Higher temperatures favor foliar development and retard tuberization. In addition, heat stress leads to a higher number of smaller tubers per plant, lower tuber specific gravity with reduced dry matter content, and usually to a paler skin color of the tubers. Temmerman *et al*. (2002) [28] examined the effect of latitude, seasonal mean air temperature (ranging from 13.8 to 19.9ºC), global solar radiation (ranging from 12.0 to 21.3 MJ m-2 d-1), air humidity, soil moisture, and atmospheric CO_2 concentrations on tuber yield in European experiments. Ignoring CO_2 enrichment, the yield of potato (cv. 'Bintje') increased from south to north Europe. Marketable tuber yields increased at higher latitudes. The authors ascribed this result to lower temperatures, lower vapor pressure deficits, and longer day lengths at higher latitudes, which in turn resulted in longer effective growing seasons. Climatic conditions, as affected not only by the latitude but also by altitude, influence potato plant growth and development. Moreno (1985) [29] found that plants grown at low (coastal) altitudes have low yield of tubers per plant as compared with those grown in the Andean highlands. Tubers harvested from coastally grown plants had lower free amid acid and amide contents and a higher content of tuber protein than those from the Andean highland. Coastal tubers also had less total sugar content than Andean tubers. Haverkort (1990) [27] reports that an inconvenience of the short day sensitivity of the potato is that cultivars that make use of the whole growing season and produce well in northern Europe (5-6 month growing season), may mature too early and senesce between 60 and 70 days after planting in the equatorial highlands and consequently yield less. Cultivars that perform well at low latitudes in a 3 to 4 month growing season start tuberizing late and mature too late at 50ºN.

Photoperiodic responses are mediated by endogenous plant hormones. Relatively high gibberellic acid (GA) levels reduce or stop tuber growth and relatively high abscisic acid (ABA) levels promote tuber growth. In some potato cultivars and species, long photoperiods produce high GA levels that prevent tuber growth. This can be a problem for temperate regions, which have long photoperiods during their usual crop season. Fortunately, many of the American cultivars are "day neutral" and presumably have lost the GA-photoperiod response (Dwelle, 1985) [30, 42]. Carbon dioxide concentration can also exert a strong influence on potato productivity. The influence of carbon dioxide depends on solar irradiance (Wheeler *et al*.,1991) [31]. Potato (cultivars 'Norland', Russet Burbank, and 'Denali') were grown at CO2 levels of 350 or 1000 µmol mol-1, irradiance of 400 or 800 µE m-2 s-1 photosynthetic photon flux (PPF), and photoperiod of 12 or 24 hours-light. Increased CO2 provided greater tuber yield at low PPF but decreased tuber yields at high PPF. Increasing the PPF increased the tuber yield for Denali but decreased the yield for Russet Burbank. When averaged across all irradiance treatments, Denali showed the greatest gain in tuber and total weight (21 and 18%, respectively) in response to increased CO2 enrichment for the three cultivars tested. Norland showed the least (9 and 9%, respectively), while Russet Burbank showed an intermediate response, with gains nearly as great as for Denali under a 12 h-photoperiod (18%) but less than Denali under a 24 h-photoperiod. A pattern of greater potato plant growth was observed from CO_2 enrichment under lower PPF and a short photoperiod. Crop growing systems for space travel are needed to generate oxygen, purify water, remove carbon dioxide, produce food, and recycle waste materials. Total irradiance has been suggested to be the largest limitation to crop productivity in these systems. Potato yield improvements might be obtained by increasing the net daily photosynthetically active radiation (PAR) through higher irradiance or longer photoperiod (Stuttle *et al*., 1996) [32]. The photoperiod duration doubles from December to June at 50oN, while PAR increases eightfold from 211 to 1701 MJ m-2 d-1 due to higher elevation of the sun above the horizon with lengthening days. Gross carbohydrate production on standard clear days increases from 108 to 529 kg ha-1 d-1 at 50oN, whereas it remains at about 420 kg ha-1 d-1 year-round near the equator. Low solar irradiance is a yield constraint at 30 to 40oN in winter when potatoes are grown to escape the summer heat (Haverkort, 1990) [27]. Stuttle *et al*. (1996) [32] studied the effect of photoperiod (12, 18, and 24 h-light) on net carbon assimilation rate (Anet) and starch accumulation in newly mature canopy leaves of Norland potato under low and high PPF, 263 and 412 µE m-2 s-1, respectively. Whenever the photoperiod was increased from 12 to 18 hours, there was a marked decline in Anet of 16.1%, and declines were most pronounced under high PPF. The maximum starch concentrations were obtained under high PPF treatments at a shorter photoperiod than under low light treatments. An apparent feedback mechanism exists for regulating Anet under high PPF, high CO2, and long photoperiod, but there was no correlation between Anet and starch concentration in individual leaves. This suggests that maximum Anet cannot be sustained with elevated CO2 enrichments under long photoperiod and high PPF conditions for Norland. Therefore, if a physiological limit exists for the fixation and transport of carbon, increasing photoperiod and light intensity under high CO2 enrichment may not maximize potato yield. Since the onset and early phases of tuber growth are important for the further development of potato, Dam *et al*. (1996) [33] conducted a factorial experiment with two photoperiods (12 or 18 h) and four 12-h day/night temperatures (18/12, 22/16, 26/20, and 30/24ºC) to analyze photoperiod and temperature effects on early tuber growth, dry matter partitioning, and tuber number for cultivars 'Spunta' and 'Desiree'. They concluded that low mean temperatures (15-19ºC) with a short photoperiod (12 h) were most suitable for early tuber growth. Under these conditions, onset of growth and onset of bulking were early, and absolute tuber growth rates and dry matter partitioning were high. Slight increases in temperature strongly reduced partitioning rates, whereas further increases had a large impact on the onset of tuber growth and absolute growth rates. Differences between treatments in numbers of tubers initiated were inconsistent. The absolute growth rate under long photoperiod was higher for Spunta than for Desiree. Different genotype responses to temperature and photoperiod on tuber growth were also found by Snyder and Ewing (1989) [34] using potato cuttings. Midmore and Prange (1992) [35] examined the effects of day/night temperature (33/25oC or 20/10oC), and 12-h high irradiance (430-450 µE m-2 s-1 PAR) or 12-h low irradiance (250-280 µE m-2 s-1 PAR) both with a 6-h photoperiod extension at 6 µE m-2 s-1 on relative growth rate, net assimilation rate, and dry matter production of Solanum goniocalyx cv. 'Garhuash Huayro' and DTO-33, a heat tolerant clone of S. tuberosum x S. phureja. The highest relative growth rate was obtained at low temperature and low irradiance. At high temperature, low irradiance had the opposite effect, producing the lowest net assimilation and relative growth rates. Both tuber number and weight were markedly reduced by high temperature. Low irradiance in combination with high temperature produced virtually no tubers. These data, consistent with field observations that reduced potato growth at high temperatures, can be aggravated by lower irradiance.

Both leaf area and net assimilation rate are reduced. Manrique and Bartholomew (1991) [36] carried out a potato genotype x environment experiment on Mt. Haleakala, Maui, Hawaii, at three elevations from 91 to 1097 m, to assess the performance of four standard temperate cultivars and three heat-tolerant clones in warm to cool temperatures at photoperiods prevailing in the tropics. Dry weight of plant components and total dry weight per plant were measured at tuber initiation, 20 days after tuber initiation, and 40 days after tuber initiation. Warm temperatures at 91 m hastened development such that, at tuber initiation, total dry weight per plant was 2 to 4 times greater than at 1097 m in 1985 and 1986 Tuber dry weight increased significantly at the second two sampling dates with lower temperature at higher elevation. Dry matter partitioning to tubers generally was highly and significantly correlated with temperature, with the optimum of 15 to 20oC for tuber growth. Potato plants lost their ability to allocate dry matter to tubers at higher temperatures. Sarquis *et al*. (1996) [37] stated that the magnitude of the effect of elevated temperatures on potato growth and final yield is determined by an intricate interaction between soil temperature, air temperature, solar radiation and photoperiod duration. Their data extended previous observations of reduction in photosynthesis rate under elevated temperatures. Under field conditions they concluded that reduced carbon assimilation rate could not explain the yield reduction observed; the temperature effect on assimilation was not as dramatic as it was on growth or yield. Other workers have reported a severe reduction in the rate of assimilation at air temperatures above 30ºC under controlled experimental conditions. In such cases, the reduction in carbon assimilation rate was shown to correlate well with reductions in growth and yield (Ku *et al*., 1977; Midmore and Prange, 1992) [38, 35]. These contrasting results reveal the complexity of plant responses to the combined effects of water and temperature stress, which inevitably occur in association under field conditions.

Thornton *et al*. (1996) [39] examined the effect of two day/night air temperature regimes (low 25/12oC, and high 35/25oC) on dry matter production of three potato clones (Russet Burbank, Desiree, and 'DTO-28') for five weeks, beginning two weeks after tuberization, under controlled environmental conditions. Tuber growth rate was more affected by high temperature than was whole plant growth. All clones exhibited a decline in tuber dry matter production at high compared to low temperatures; however, Russet Burbank exhibited the largest decline. Potato clones varied in partitioning of dry matter to tubers at high temperatures. In addition to carbon assimilation, heat stress reduced tuber yields by affecting several plant processes such as dark respiration. Although high temperature stress is a major uncontrolled factor affecting growth, development and productivity of plants, relatively little is known about genetic diversity for heat tolerance in potatoes. Tolerance to heat stress may involve many complex relationships. An adapted genotype must have a diverse and complex combination of genes for tolerance to high temperatures and for superior performance in the field (Tai *et al*., 1994) [40]. Potato cultivars and clones vary significantly in their ability to tuberize at elevated air temperatures and continuous irradiance. Tibbitts *et al*. (1992) [41] carried out two experiments under controlled environments to determine the capability of 24 highly productive potato genotypes to tolerate continuous light and high temperature. Six cultivars grew well under continuous light while three cultivars were superior to the others at high temperature. Two cultivars were well adapted to continuous light and high temperature. These evaluations were made after only 56 days of growth and further assessments should be made in longer-term productivity studies. For some crop plants, leaf angle can be important for maximizing solar radiation interception. With potato cultivars that are intercepting as much as 95% of incident solar radiation at a LAI of 4, one must question whether alterations in leaf angle would significantly improve light interception. Individual leaves can utilize only 50-60% of incident radiation on a clear day. Following tuber initiation, the photosynthetic apparatus saturates by about 1200 μE m-2 s-1, or about 60% of full light. Ideally, the top leaves of a potato canopy should absorb no more than 1200 μE m-2 s-1 and should allow the remaining light to pass to the lower canopy (Dwelle, 1985) [30, 42]. Opportunities remain to modify potato plant architecture to increase productivity (Hawkins, 1982) [43]. Gawronska and Dwelle (1989) [44] studied the effect of high light levels (maxima between 500 and 1200 μE m-2s-1) and shaded low light levels (approximately one-quarter of the high light) on potato plant growth, biomass accumulation and its distribution. They observed that plants under low light did not produce auxillary shoots, while those under high light did. Tubers of plants under low light were very small and irregular in shape. The most evident plant response to low light was greater stem elongation as well as a reduction in total biomass accumulation and in tuber weights. The reduction in total biomass under low light was 34 to 45%. Reduction in tuber dry weights under low light ranged from 39 to 57%, depending on the growth stage and harvest time. In addition, at all growth stages, the percentage of biomass partitioned to the tubers was higher under high light than under low light conditions.

According to Gawronska *et al*. (1990) [45], potato plants grown under low light generally had lower rates of photosynthesis (when compared with those grown under high light), reaching saturation for maximum photosynthesis at about 500 μE m-2 s-1.Some clones maintained the higher rates of photosynthesis than Russet Burbank at nearly all-light levels, demonstrating the potential to breed for cultivars that maintain higher rates of photosynthesis and potentially higher tuber yields.

Soil Temperature

The rate of development of sprouts from planted seed pieces depends on soil temperature. Very little sprout elongation occurs at 6°C. Elongation is slow at 9°C and is maximized at about 18°C. The time between planting and emergence depends on soil temperature. Phytotron and field experiments carried out by Sale (1979) [47] showed that emergence was linearly related to mean soil temperature and relatively independent of diurnal fluctuations up to an optimum of 22-24oC. Up to this optimum emergence could be considered as a degree-day requirement calculated either from soil temperature at tuber depth or air temperature. At temperatures above the optimum, emergence was inhibited. Sattelmacher *et al*. (1990) [48] studied the effect of 20 ºC and 30 ºC root-zone temperatures on root growth and root morphology of six potato clones. Significant genotypical differences in the responses of potato roots to 30 ºC were observed, indicating the potential for selecting heat tolerant potato clones. In both heat tolerant and heat sensitive clones, the size of the root system was reduced by a 30 ºC root-zone temperature explained by a reduction in the cell division followed by cessation of root elongation. Tuberization stimulus favors both tuber initiation and tuber enlargement. Through artificially prolonged exposure to short days and cool temperatures, it is possible to attain such a high level of stimulus that induction is irreversible, even if potato plants are subsequently exposed to long days for weeks or months. The optimum soil temperature for initiating tubers ranges from 16 to 19°C (Western Potato Council, 2003). Reynolds and Ewing (1989) examined the influence of four air and soil day-night temperature treatments on root, tuber, and shoot growth in growth chambers: (cool air (19/17ºC), with cool or heated soil (20/18ºC or 32/31ºC); and hot air (34/30ºC), with hot or cooled soil (32/27ºC or 19/17ºC)). Cooling the soil at high air temperatures neither relieved visible symptoms of heat stress on shoot growth nor increased the degree of induction tuberization by the leaves. Heating the soil at cool air temperatures had no apparent detrimental effect on shoot growth or induction of tuberization by the leaves. Under high soil temperatures, stolonization was substantially compromised and there was no underground tuber development. In one experiment, stolons grew up out of the hot soil and formed aerial tubers above the soil surface in the cool air. The induction of tuberization by the leaves was affected mainly by air rather than soil temperature, but the signal to tuberize might be blocked by high soil temperatures. According to Mares *et al*.(1985), it is expected that the effect of high soil temperature on growing tubers would be similar to that of exogenously applied gibberellin, inhibiting tuberization.Tuber development declines as soil temperatures rise above 20°C and tuber growth practically stops at soil temperatures above 30°C. The number of tubers set per plant is greater at lower temperatures than at higher temperatures, whereas higher temperatures favor development of large tubers (Western Potato Council, 2003). Little research is available on the effect of soil temperature during tuber growth on potato grade and quality. Kincaid *et al*. (1993) [51], assessing the influence of the interaction between water management and soil temperature on potato quality in the Pacific Northwest, observed that the critical period for tuber quality appears to be from mid-June to mid-July, based on measured soil temperature differences, frequent sprinkler irrigation reduced soil temperatures, along with the incidence of sugar-end tubers. Yamaguchi *et al*. (1964) [52] found that yield, specific gravity and starch content of Russet Burbank and 'White Rose' tubers were higher, and the sugar content lower when grown at soil temperatures between 15 and 24oC, than when grown at higher temperatures. Ewing (1981) [53] reports that in many areas the sequence of temperatures that most often brings economic damage to potato crops is warm temperatures early in the season, followed by cool temperatures that induce strong tuberization, followed in turn by another period of high temperatures. Such temperature oscillations lead to heat sprouts, chain tubers, and secondary growth of tubers. Apparently the fluctuations in tuberization stimulus cause tuber formation to alternate with more stolon-like growth. Management practices, such as planting population density, use of mulch and irrigation might substantially modify the soil temperature regime within the root zone in such a way as to affect stolonization, tuber initiation and bulking, and tuber enlargement at a given site, particularly where solar irradiance availability is shown to be a non limiting factor for potato production. Increase of plant population through a reduction of between-row spacing was effective in raising tuber yields in the hot tropics, largely through the increase in amounts of intercepted solar radiation, which brought about a significant decline on soil temperatures during the tuber growth. Since the proportion of marketable tubers was scarcely affected by planting densities, Midmore (1988) [55] reasoned that potato plant population in hot climates should be as high as possible without limiting the amount of soil available for hilling-up. In order to quantify the effects of organic mulch on soil temperature and soil moisture regimes during the growth of potato, Midmore *et al*. (1986a) [54] conducted seven experiments at three contrasting hot tropical sites (latitude varying from 5 to 12ºS, and altitude ranging from 180 to 800 m). Mulch retained more heat in the soil at night when combined with agronomic practices that themselves increased soil heat retention at night (i.e. on the flat potato beds). The magnitude of soil cooling by mulch during the day and heat retention within the soil at night was dependent on solar irradiance levels and soil moisture content. Mulch was more effective in cooling dry soils, especially at high irradiance. Heat retention at night following days of low irradiance was greater in mulched plots, whereas at high irradiance heat retention of mulched plots was intermediate between those of moist and drier control plots. Midmore *et al*. (1986b) [56] showed that mulch increased tuber yield by 20% during the summer in Lima, Peru. Manrique and Meyer (1984) [57], studying the impact of mulches on potato production during winter and summer seasons at the same site, found no effect on yields during the winter, but yield increases of 58% and improvements in soil moisture retention were obtained in the summer with surface mulch. Mahmood *et al*. (2002) [58] reported that mulch at Islamabad, Pakistan, decreased daily maximum soil temperature at a 15 cm-depth by 1.5 to 4.5ºC, resulting in faster emergence, earlier canopy development, and higher tuber yields. Many other recent studies conducted in Asia point out the beneficial effects of mulch in potato production systems as an efficient alternative to obviate heat and water stresses in order to maximize crop yield (Jaiswal, 1995; Ruiz *et al*., 1999; and Sarma *et al*., 1999) [59-61].

Atmospheric CO2

Climate change is projected to reduce potato yields approximately by 2.5, 6 and 11 per cent in the IGP region by 2020 (2010-2039), 2050 (2040- 2069) and 2080 (2070-2099) respectively (Kumar *et al*., 2015) [3, 9]. Singh *et al*., (2013) [4] revealed that elevated CO2 (550 ppm) produced a beneficial effect in tuber yield (+11.1%) up to a temperature increase of +1°C but when the temperature increment reached a threshold of +3°C even the elevated CO2 caused a reduction of 13.7 per cent. in tuber yield.

Table 1: Impact of climate change on tuber productivity in major potato growing states of India without adaptations under optimal management (2020:1 ºC, 393 ppm; 2050:3 ºC, 543 ppm)

States	Change (per cent) from current productivity	
	Future Climate (Year)	
	2020	2050
Uttar Pradesh (UP)	-1.61	-9.08
West Bengal (WB)	-4.86	-16.11
Bihar	-3.01	-11.50
Punjab & Haryana	-7.31	-3.66
Madhya Pradesh (MP)	-6.64	-20.63
Gujarat	-16.75	-55.10
Maharashtra	-8.82	-35.29
Karnataka	-18.68	-45.73

***Source*:** Singh *et al.* (2009) [8, 24]

Fleisher *et al.* (2016) [62] pointed out that temperature is more important source of uncertainty in potato crop models than CO2 and water. In northern states like Punjab and Western Uttar Pradesh, which currently have the lowest average minimum temperatures, are not expecting increase in temperature, and some authors expect increase in rainfall as a result, potato production may be benefitted in those regions. Nonetheless, in Punjab, in addition to the monsoon, farmers also utilize groundwater sources for irrigation and there is evidence of overexploiting this resource and further depletion of groundwater may reduce the benefits of the increase rainfall (Baweja *et al.*, 2017) [63].

Atmospheric Humidity and Wind: There are very few recent studies dealing with the direct effects of relative humidity (RH) on potato growth, tuber yield and grade. Most of the contributions related to the influence of RH on potato refer to potato storage where RH is an important factor in tuber weight loss and the occurrence and severity of diseases and pests. The same scarcity of research exists with regard to the wind regimes at a particular location as an agrometeorological factor affecting potato production systems. Wheeler *et al.* (1989) [64] studied the effect of two RH levels, 50% and 85%, on the physiological responses of three cultivars of potato (Russet Burbank, Norland, and Denali) in controlled-environment rooms under continuous light intensity at 20ºC. No significant differences in total plant dry weight were measured between the atmospheric humidity treatments, but plants grown under 85% RH produced higher tuber yields. Leaf areas were greater under 50% RH and leaves tended to be larger and darker green under drier than at more humid atmospheric conditions. The elevated humidity appeared to shift the allocation pattern of photosynthates to favor allocation to the tubers over leaves and stems. Gordon *et al.* (1999) [65] estimated sap flow from solar radiation and vapor pressure deficit data for three field-grown potato cultivars (‘Atlantic’, ‘Monona’ and ‘Norchip’) at Nova Scotia, Canada, under non-limiting soil water conditions. Sap flow rates for all cultivars were closely linked with solar radiation under conditions where soil water was not limiting. The vapor pressure deficit (VPD), a function of relative humidity and air temperature, had less effect on sap flow, although the magnitude of the VPD during the growing season was generally < 2 kPa. All cultivars maintained actual daily transpiration near the potential energy limiting rate under well-watered conditions. When the soil was drier (percent available soil water < 30%), Monona potato plants had a much more rapid decline in transpiration than the other two cultivars. Another physiological parameter closely related to yield is water use efficiency. Bowen (2003) [1, 22] reported that potato arming in coastal Peru occurs during the winter, when the cool humid conditions favor growth and promote a more efficient use of irrigation water. During the winter, less soil water evaporation caused by a smaller VPD enhances water use efficiency when compared with that observed during the summer. Sinclair (1984) [66, 77] also showed that generally more humid environments provide greater water use efficiency because of a lower VPD. Stomatal resistance governs photosynthesis and transpiration. Two major feedback loops are reported by Raschke (1979) [67] as the direct controllers of stomatal resistance (rst). The first involves photosynthesis where a reduction in intercellular carbon dioxide (CO2) occurs as the photosynthetic active radiation (PAR) increases, the stomata open and rst decreases. The second involves an increase in rst whenever leaf water potential reaches a critical threshold as a result of transpiration intensity. Stomatal resistance is affected by many factors including PAR, the ratio of leaf to air water potential, leaf age, air temperature and the ambient CO2 concentration (Kim and Verma, 1991) [68]. Gordon *et al.* (1997) [46] studied the stomatal resistance of three field grown potato cultivars (Atlantic, Monona and Norchip) in response to photosynthetic photon flux density, leaf to air vapor pressure difference and root zone available water. Under the climatic conditions of their field experiment in Eastern Canada, stomatal activity in potato was primarily driven by light intensity. However, as soil water became limiting the soil/plant water status became increasingly more important. The absence of very high VPD values throughout the growing season is the probable main reason for the lack of potato rst response to air vapor pressure differences. Significant differences were observed among cultivars in the response of stomata to changes in available soil water. Crop weather modeling needs to incorporate these differences into model systems because they might have a significant effect on eventual model performance at a given site. Wind has important effects on potato. Pavlista (2002) [70] reported that leaves injured by lower wind speeds show bronzed areas, brown with a shiny surface, due to the rubbing of leaves against each other. The bronzed areas tend to brittle from drying. When pressed the bronzed areas crack, forming a sharp-edged rip through the affected tissue. Under higher wind speeds, leaves not only bronze but also tatter. Tattered leaves typically have a 6 to 25 mm sized tears with irregular brownish borders. Stems may also be affected by winds. When exposed to a mild wind, stems may just be flopped around causing a slight weakness of the tissues. Under strong winds, vines might actually get twisted, bringing about a break or hinge-like weakness in the stems. If exposed to strong winds for several hours, the vine may twist all the way around and cause the stem to collapse, cutting off nutrient flow through the phloem between the vine and the tubers. Wind also affects transpiration rates and, therefore, photosynthetic activity and crop yield. At sites where winds are frequently strong throughout the year, increased stomatal resistance can cause reduction in potato yield (Pavlista, 2002; Sun and Dickinson, 1997) [70, 71]. At such sites, guidelines for the sustainable management of potato cropping systems need an emphasis on windbreak development including height, porosity, and orientation. Sun and Dickinson (1997) [71] studied the benefit of two 30-month-old windbreaks (one with two rows of trees and one with three rows of trees) for potato in tropical northeastern Australia. Two Eucalyptus species (E. microcorys and E. torelliana) were found to be highly suitable for windbreaks since they showed rapid development in height and branch growth while retaining low branches. The porosity of three row and two row windbreaks were 37.2 and 60%, respectively. The optimum range of porosity for windbreaks is between 40 and 50% (Marshal, 1967) [72]. Windbreaks increased potato plant growth in height and leaf number, however, had limited effects on leaf length and width. Potato plants grown close to windbreaks yielded more than those grown at the furthest positions, with the highest production removed 3 times the windbreak height. Windbreaks increased potato yield by up to 7.7%, whereas Sturrock (1981) [73] found windbreaks increased yield by 35%. Wright and Brooks (2002) [74] examined the effect of windbreaks on growth and yield of potatoes over a 4-year period in Australia, measuring the amount and severity of wind damage to leaves, plant height, and leaf numbers from potato located at various distances from the windbreak in both sheltered and unsheltered positions. Windbreaks increased tuber yield between 4.8 and 9.3% for the sheltered portion of the field in seasons with higher than average wind speeds and caused a reduction in wind damage to leaves on protected potato plants. In seasons where wind speed was above average, windbreaks increased yield at distances away from the windbreak between 3 and 18 times the eight of the windbreak. Cleugh (2003) [75] reported that potato crop yields were significantly higher in the sheltered zone from 2 to 18 times the height of the windbreak compared to yields obtained in unprotected areas.

Climate change and diseases of potato

Plant diseases are one of the important factors which have direct impact on global agricultural productivity and climate change will further aggravate the situation. Plant diseases are estimated to cause yield reduction of almost 20 per cent in the principal food and cash crops worldwide (Thind, 2012) [75]. The potato is prone to more than hundred diseases caused by bacteria, fungi, viruses and mycoplasmas. However, *Phytophthora infestans*, *Alternaria solani*, *Rhizoctonia solani*, *Sclerotium rolfsii*, *Streptomyces* spp., *Ralstonia solanacearum*, and several virus pathogens have been observed responsible for degeneration and deterioration of potato crop as well as yield losses to crop (Shekhawat *et al*., 1993) [76]. Different pathogens prevail in different regions depending on the geographical limits of any area (Table 2). Changes in temperature and precipitation regimes due to climate change may alter the growth stage, development rate and pathogenicity of infectious agents, and the physiology and resistance of the host plant (Chakarborty and Datta, 2003) [78, 116]. A change in temperature could directly affect the spread of infectious diseases and their survival between seasons (Table 3). Major climate change factors likely to influence plant disease severity and spread include elevated CO_2, heavy and unseasonal rains, higher humidity, drought, cyclones and hurricanes, and elevated temperature (Luck *et al.*, 2011) [79].

Late Blight of Potato

Potato late blight is an important disease caused by the *Phytophthora infestans* (Mont.) De Bary. Late blight is well-known for its role in the Irish potato famine and its current threat to potato production globally. Potato yield losses from diseases, animal pests and weeds were estimated to be around 40 per cent of attainable production, with diseases alone accounting for 21 per cent (Oerke, 2006) [80], out of which potato late blight is generally recognized as the most important potato disease. Late blight has been known as weather driven disease which has led to the development of weather-based forecasting models that assist farmers in scheduling fungicide applications. Andrade-Piedra *et al.* (2005) [81] using a meta modelling approach demonstrated that late blight was very sensitive to changes in temperature and relative humidity, which could be critical factors in determining the role that late blight might play in a potato system's robustness against climate change (Hijmans *et al.*, 2000) [82]. Late blight scenario in India would also change drastically with climate change. Currently, late blight is not a serious problem in autumn in the state of Punjab, Haryana and parts of Uttar Pradesh, primarily due to sub-optimal temperature regimes during December-January. However, disease outbreaks are expected to become more intense with increase in ambient temperature coupled with high relative humidity. Such scenarios were witnessed during 1997-98 and 2006-07, when average crop losses in this region were over 40 per cent. Increase in ambient relative humidity would have a far greater impact of late blight outbreaks in the country. Here, the crop is grown totally under irrigated conditions. Luck *et al.* (2012) [83] assessed the influence of climate change on potato production and potato late blight was assessed using two climatically distinct potato growing regions each in India's West Bengal (Nadia and Hooghly) and Bangladesh (Bogra and Munshiganj). Regional climate projections to the year 2050 were obtained for each location using IPCC climate scenario A1B for West Bengal and Bangladesh. Two regional forecasting models indicated an increasing trend (+0.2 to +0.6°C) for maximum and minimum temperatures by 2050. An increasing trend in rainfall was expected for 2050 but no difference in solar radiation was predicted compared to 1981-2010 data. The impact of climate change on potato production in the study areas in India and Bangladesh showed yield decline of 23-32 per cent by 2050. To assess the effect of climate change on Potato Late Blight, nine published models were tested for accuracy against ten years of West Bengal disease incidence records. The best model was only 25 per cent accurate in predicting Late Blight outbreaks for that time period and, therefore, an alternative approach was developed by adapting the Jhulsacast model and applying fog-based rules. When climate change projections were incorporated, this modified model showed that the onset of Late Blight is likely to be earlier in the growing season for 2031-2040 but severity is likely to be 5-7 per cent less than 1981-2010 records in the intensive potato growing areas of West Bengal. However, in northern Bangladesh, disease severity is predicted to increase by up to 12 per cent, and reduce by 7 per cent in central Bangladesh.

Table 2: Distribution of potato diseases among different states of India

Sr. No.	Name	Causal Organism	States	Reference
		Fungal Diseases of Potato		
1	Late Blight of potato	*Phytophthora infestans*	Punjab, Haryana, Uttar Pradesh, Maharashtra Bihar, West Bengal, Karnataka	Mohan and Thind, 1999 [84] Bhat *et al.*, 2010 [85]
2	Early Blight of potato	*Alternaria solani*	Uttar Pradesh, Madhya Pradesh, Andhra Pradesh and Maharashtra	Singh and Gupta, 1953 [86]
3	Wart Disease	*Synchytriumendobioticum*	West Bengal, Darjeeling hills	Singh, 1998
4	Black scurf / Canker	*Rhizoctonia solani*	Himachal Pradesh, Uttar Pradesh, Uttrakhand, Sikkim, Assam, Maharashtra, Madhya Pradesh	Verma *et al.*, 1990 [87], Khurana *et al.*, 1998 [88] and Bains *et al.*, 2002 [89]
5	Charcoal rot	*Macrophominaphaseolina*	Uttar Pradesh, Himachal Pradesh, Uttarakhand	Rao and Mukerji, 1972 [90]
6	Dry rot	*Fusarium species*	Madhya Pradesh, Haryana	Sagar *et al.*, 2011
7	Wet rot	*Sclerotiumrolfsii*	Uttar Pradesh, Maharashtra, Madhya Pradesh, Himachal Pradesh, Uttarakhand	Madhavi and Bhattiprolu, 2011 [92] Banyal *et al.*, 2008 [93]
		Bacterial diseases of potato		
8	Common Scab	*Streptomyces scabies*	Khasi Hills (Meghalaya), West Bengal, Himachal Pradesh	Paharia and Pushkarnath, 1963 [94]
9	Bacterial Wilt	*Rolastonia solanacearum*	Trivandrum, Assam, Orissa, Karnataka, West Bengal, Uttar Pradesh, Punjab, Haryana, M.P., Chhattisgarh	Anonymous, 1981 [95]
		Viral diseases		
10	Mosaic disease	Potato virus X Potato virus Y	Himachal Pradesh, Karnataka, West Bengal, Uttar Pradesh, Punjab, Haryana, M.P., Chhattisgarh, Bihar, Sikkim, Maharashtra M.P., U.P., Punjab, Bihar	Khurana, 2004 [96] Khurana, 2004 [96]

Table 3: Climatic requirement of different diseases of potato

Sr. no	Name	Causal organism	Optimum climatic requirement	Reference
		Fungal Diseases of Potato		
1	Late Blight of potato	*Phytophthora infestans*	Range:10-27 °C RH> 90% Range:14-27 °C Night temperatures: 10-16 °C with light rain, fog or heavy dew Day temperature: 16-13 °C with high relative humidity	Zwankhuizen and Zadoks, 2002 [97]; Luck *et al.*, 2012 [83] Kirk *et al.*, 2013 [98]
2	Early Blight of potato	*Alternaria solani*	Range:10-35 °C RH> 90% Range:13.5-24 °C Rainy weather with RH>90%	Rotem 1974; Johnson *et al.*, 2015 [100]
3	Wart Disease	*Synchytriumendobioticum*	Soil Moisture: 100% Infection is favoured when temperatures are between 14 and 24 °C	Singh 2000 [101]
4	Black scurf / Canker	*Rhizoctoniasolani*	Soil temperature: 16-23 °C Soil: Dry Air temperature: 18-28 °C	Lui 2001 [102]; Frohning 2013 [103]
5	Charcoal rot	*Macrophomina phaseolina*	Ambient temperature: 30 °C or above	Somani 2007 [104]
6	Powdery Scab	*Spongosporasubterranea*	16–17ºC and that the minimum and maximum temperatures were <11oC and 22–25oC respectively	Kole 1954 [105]
7	Dry rot	*Fusarium species*	Range: 25-35 ºC RH: 90-98%	Theron and Holz 1990 [106]
		Bacterial diseases of potato		
8	Common Scab	*Streptomyces scabies*	Optimal soil temperature: 19-24 °C With low moisture level	Healy and Lambart 1991 [107]
9	Wet rot	*Sclerotium rolfsii*	Range: 4-37 °C Cool to moderate maximum daily temperatures (29 °C) and moisture from rain, fog, dew, or high relative humidity. Viral diseases	Duarte *et al.*, 2004 [108] Workneh and Yang 2000 [109]
10	Mosaic disease	Virus	Temperatures of 16 to 20o Cwith cloudy weather	Sutic *et al.*, 1999 [110]

Early blight of potato

Early blight caused by *Alternaria solani* is influenced by temperature and relative humidity. High temperature and relative humidity favour its outbreak. Such situation mostly exists in plateau and sub-mountainous regions, although, it is known to infect potato crop throughout Indo-Gangetic plains as well as high hills. The disease is most favoured by temperature ranging from 25 to 30 °C with an optimum of 26 °C (Dutt, 1979) [111] prevailing temperatures in the foothills and plateau are already high. Further warming may not lead to any substantial effect on the disease. However, altered precipitation, especially above normal, may favour the disease development in nitch areas.

Soil borne diseases

A large number of soil borne pathogens attack potato crop. Some of the important ones include, *Synchytrium endobioticum* causing wart, *Spongospora subterranea* causing powdery scab, *Rhizoctonia solani* (black scurf and canker), *Streptomyces scabies* (common scab), *Sclerotium rolfsii* (sclerotium wilt), *Macrophomina phaseolina* (charcoal rot), *Rolastonia solanacearum* (bacterial wilt) and *Fusarium spp*. (wilt and dry rots). Some of them *viz*. *S. endobioticum* and *S. subterranea* are favoured by low temperature and high soil moisture whereas remaining ones are favoured by moderate to high temperature and low soil moisture. Consequently, the effect of climate change would also vary from pathogen to pathogen. Although, wart spores can cause infection in the range of 10 to 28 °C with an optimum of 21 °C but there is hardly any infection beyond 23 °C. Therefore, warmer climates are likely to reduce wart infestation. Similarly, reduced precipitation will also lower down wart infestation as it requires 100 per cent soil moisture for infection to occur. Powdery scab infestation is also likely to be reduced with increase in temperature and reduction in rainfall as a consequence of global warming. Since optimum temperature for powdery scab is 12 °C, and moisture requirement is 100 per cent, the global warming may either lead to elimination of this disease or it will be pushed to higher altitudes making high hills free of powdery scab. Diseases like *sclerotium* wilt, charcoal rot and bacterial wilt are favoured by high temperature and moisture. *Sclerotium* wilt in India is restricted to plateau regions (M.P., Karnataka, Maharashtra). Optimum temperature requirement for this disease is 30-35 °C. With the increase in temperature due to global warming, the disease may enter into other areas like mid hills, and in long run, it may also become prevalent in eastern Indo-gangetic plains. Similarly, bacterial wilt may also advance to higher altitudes in hilly regions due to global warming.

Charcoal rot is currently endemic in eastern U.P., Bihar and M.P. The global warming is likely to increase the severity of this disease in these regions. It is also likely to expand to other parts of North Central plains as well. Black scurf and common scab are favoured by moderate temperatures (15-21°C and 20-22°C, respectively) and are likely to remain insulated from global warming in near future. By the end of the century, when ambient temperatures are likely to increase by 1.4 to 5.8 °C, the severity of these two diseases may decrease substantially. Virus diseases are bane to potato production world over, but more so in subtropics and tropics. The rate of multiplication of most of the potato viruses gets increased with the increase in temperatures. This is the reason why viral diseases are not so damaging in the temperate world. But, global warming may change the entire scenario of potato viruses in temperate world. Hilly regions are considered best for potato seed production but it may not be the case after 2-3 decades. Sup-tropical plains, where majority of the potatoes are grown, represent a different scenario. Although, global warming may not affect potato viruses directly, but may have a serious repercussion through the altered biology of insect vectors. The increase in temperature will enhance vector population thereby increasing the number of insecticide sprays for keeping the vector population in check (Singh and Bhat, 2008).

Climate change is predicted to have a direct impact on the occurrence and severity of diseases in crops, which will have a serious impact on our food security. Climate change will lead to rise in temperature and carbon dioxide levels and will also have a varied effect on moisture. In many cases, temperature increases are predicted to lead to the geographic expansion of pathogen and vector distributions, bringing pathogens into contact with more potential hosts and providing new opportunities for pathogen hybridization (Baker *et al*., 2000; Braiser, 2001) [113, 114]. Pathogen evolution rates are determined by the number of generations of pathogen reproduction per time interval, along with other characteristics such as heritability of traits. Temperature governs the rate of reproduction for many pathogens. Longer seasons that result from higher temperatures will allow more time for pathogen evolution. Pathogen evolution may also be more rapid when large pathogen populations are present, so increased overwintering and over summering rates will contribute as well. Climate change may also influence whether pathogen populations reproduce sexually or asexually; in some cases, altered temperatures may favour overwintering of sexual propagules, thus increasing the evolutionary potential of a population. Analysis of the last 30 years historical weather data from different locations of Punjab has indicated that significant changes have occurred in the weather causing early warming in February. In potato, economic production is often impossible without the application of pesticides. Late blight of potato is considered to be the most economically important disease of potato worldwide. The disease can destroy potato crop within a few weeks. Estimates of losses to late blight in developing countries vary between US$ 3 and US$ 10 billion each year, and about US$ 750 million is spent on pesticides alone. In the temperate Indian hills which occupy about 20 per cent of the acreage, a severe epiphytotic (epidemic) of late blight recurs every year resulting in 40–85 per cent yield loss. The disease now appears earlier in the northern part (November) and later in the eastern part (February) and within altered temperature range, i.e. 14-27.5ºC than at 10-25ºC recorded in earlier years (Luck *et al.*, 2012) [115]. In effective disease management strategy in potato, pesticide usage may increase if changing crop physiology interferes with the uptake and translocation of pesticides or changes in other climatic factors (e.g. more frequent rainfall, washing away residues of contact pesticides) indicate that there is a need for more frequent applications. Faster crop development at increased temperature could also increase the need for application of pesticides. The range of many pathogens is limited by climatic requirements for infection and development. However many studies have indicated their geographical expansion in view of climate change and warming scenarios (Chakarborty and Datta., 2003; Evans *et al*., 2007) [78, 116].

The concentration of CO_2 in the atmosphere has reached about 410 ppm at present, which exceeds the natural range of values of the past 650,000 years. Increase in CO_2 levels may encourage the production of plant biomass. However, productivity is regulated by the availability of water and nutrients, competition against weeds and damage by pests and diseases. Thus, an increase in biomass can modify the microclimate and affect the risk of infection. In general, increased plant density will tend to increase leaf surface wetness duration and regulate temperature, and thus causing infection by foliar pathogens more likely (Yanez-Lopez *et al.*, 2012) [118]. Some workers suggest that elevated CO_2 concentration and climate change may accelerate plant pathogen evolution, which can affect virulence. Under elevated CO_2 conditions, potential dual mechanism of reduced stomatal opening and altered leaf chemistry results in reduced disease incidence and severity in many plant pathosystems where the pathogen targets the stomata (Mcelrone *et al.*, 2005) [119].

Similarly, moisture can impact both host plants and pathogens in various ways. Some pathogens such as apple scab, late blight and several vegetable root pathogens are more likely to infect plants with increased moisture content because forecast models for these diseases are based on leaf wetness, relative humidity and precipitation measurements. Other pathogens like the powdery mildew species tend to thrive under conditions with lower (but not low) moisture (Coakley *et al.*, 1999) [120]. Condition of drought is also expected to lead to increased frequency of tree pathogens due to indirect effects on host physiology (Desprez *et al.*, 2006) [121]. More frequent and extreme precipitation events that are predicted by some climate change models could result in longer periods with favourable pathogen environments. Host crops with canopy size limited by lack of moisture might no longer be so limited and may produce canopies that hold moisture in the form of leaf wetness or high-canopy relative humidity for longer periods, thus increasing the risk from pathogen infection (Coakley *et al.*, 1999) [120].

Climate Change Adaptations

Changing crop productivity and disease scenario in potato due to climate change has highlighted the need for better agricultural practices and use of eco-friendly methods in yield and disease management for sustainable crop production (Boonekamp, 2012) [122]. In the changing climate and shift in seasons, choice of crop management practices based on the prevailing situation is important. In such scenarios, weather-based disease monitoring, inoculum monitoring and rapid diagnostics would play a significant role. There is a need to adopt novel approaches to counter the adverse climatic conditions and resurgence of diseases under changed climatic scenario. Different adaptation strategies are discussed as following:

Improved cultivars

It is an important strategy to adapt to the negative implications associated with climate change. In India, Pradel *et al.*, (2019) [123] analyzed the extent to which the potato sector is resilient to climate change. State-level climate change projections were compared with adoption of high resistant and tolerant potato varieties to major abiotic and biotic stresses. Release and adoption data was collected in 2016 in six expert elicitation workshops conducted with 130 experts from the potato value chain in Bihar, Gujarat, Karnataka, Punjab, Uttar Pradesh, and West Bengal. They observed that from 81 releases, 45 improved varieties are adopted in India and that in each state high resistant and tolerant varieties are cultivated providing some degree of varietal resilience. Early maturity has been the most important and heat tolerance is the least important trait. Punjab has the most balanced resilience in comparison to other states. High drought tolerance, late blight resistance, and early maturity are found in adopted varieties. Despite the heat tolerant index being very low, the state is predicted to become warmer, which will favour potato production. Heat tolerance is thus of less importance. Similarly, due to expected increases in (extreme) rainfall, droughts are unlikely to become an issue for potato production in Punjab. Under changing climatic scenario of Punjab, late blight can remain as an issue with a current late blight resistance index (LBI) of 0.57.One of the important climate change adaptation strategy is to breed drought and salinity tolerant cultivars. Exotic cultivars like Rutt and Haig are reported to initiate tubers at continuous exposure to as high temperature as 30°C. Mining for biodiversity to heat tolerance is on priority.

Table 4: Effect of adaptation through change of planting date on potato production in India

Location: Indo- Gangetic Plains	**Date of Planting**		**Change (per cent) in yield**	
		Current	**2020**	**2050**
Jalandhar (Punjab)	-5	-5.6	6.7	-3.4
	Optimum (Nov 1st)	0.0	7.3	3.7
	+5	15.1*	18.1	13.8
	+10	19.4*	21.7	18.9
Burdwan(West Bengal)	-5	-1.4	-7.5	-19.8
	Optimum (Mid Nov)	0.0	-3.9	-7.7
	+5	-8.6	-9.4	-15.5
	+10	-15.0	-19.6	-24.1

Source: Singh *et al.* (2009) [8, 24]

There are number of techniques which can be used to modify microclimate and save crop from harsh weather effects. For example, mulching can raise the content of organic matter in the soil. This, in turn, increases the soil water holding capacity, thus reducing runoff and erosion and making more water available to plants. Sustainable water use can also be achieved through improved irrigation systems, one example of which is drip-irrigation. Such systems need not be expensive. In some developing countries such as, for example, India, low-cost micro-irrigation systems are produced locally and at a relatively moderate price. Conservation tillage and on farm crop residue management. Singh and Ahmad (2008) [125] concluded that mulching had significant influence on potato growth and yield. Emergence, plant height and number of stems improved with black polythene mulching at Leh (Ladakh). Maximum tuber yield

(35.2 t ha-1) was recorded with black polythene mulching followed by white polythene.

Weather based insurance

Insurance against adverse weather is required for the cash crop of potato with high cost of cultivation. Effective crop insurance schemes should be evolved to help farmers in reducing the risk of crop failure due to these events. Both formal and informal, as well as private and public, insurance programs need to be put in place to help reduce income losses as a result of climate-related impacts. However, information is needed to frame out policies that encourage effective insurance opportunities.

Conclusion

Agroclimatic conditions greatly influence the cultivar choice, agronomic husbandry practices and the economics of production. Potato production in most regions is becoming more sensitive to climate change, which is manifested by high fluctuations in the quantity and quality of potato yield due to high damage like crop decay, increased cost of replanting, increased pest and diseases, increase cost of production as well as increased soil erosion, which are caused by increasing temperatures, drought and floods resulting from excessive rainfall. Therefore agriculture must transition to more productive, resilient, and sustainable processes to cope with the changing climate.

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