Climate change effects on the global risk of potato late blight

Running title: Climate change effects on potato late blight

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Abstract

Weather affects the severity of many plant diseases, and climate change is likely to alter patterns of crop disease severity. Evaluating such future patterns can help in prioritizing crop breeding and disease management research efforts. We modeled the global effect of climate change on potato late blight, a disease infamous for its role in the Irish potato famine that continues to be an important limiting factor for potato production around the world. We used a newly developed disease metamodel, and considered five general circulation models and three greenhouse gas emission scenarios. We found that the average global risk of potato late blight increases initially under all three scenarios, though less so for the B1 (lower emissions) scenario. Later, estimated late blight risk declines below historical levels because there is not sufficient relative humidity to maintain infection as temperatures increase. While analyses of global disease scenarios make a number of simplifying assumptions, high temperatures may be an important limiting factor in the future for many foliar diseases such as late blight.

Introduction

The risk of damaging levels of many crop diseases, referred to hereafter simply as 'disease risk', is strongly influenced by the weather. Infectious plant disease occurs due to the interaction of three factors: a favorable environment, a susceptible host, and a competent pathogen (“the disease triangle” (Madden *et al.*, 2007)). Therefore, changes in weather due to climate change are likely to affect disease risk (Anderson *et al.*, 2004, Coakley *et al.*, 1999, Garrett *et al.*, 2006) and the effects of plant disease on crop production (Hijmans, 2003). There is growing interest in plant disease risk under future scenarios (Luck *et al.*, 2011, Chakraborty *et al.*, 2011, Pautasso *et al.*, 2010, Sutherst *et al.*, 2011, Juroszek *et al.*, 2011, Savary *et al.*, 2011) and how to adapt disease forecasting models to new scales of application for scenario analysis (Seem, 2004, Seem *et al.*, 2000, Garrett *et al.*, 2011, Shaw *et al.*, 2011).

Potato late blight is an important crop disease caused by the oomycete *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 loss from diseases, animal pests and weeds was estimated to be around 40% of attainable production, with diseases alone accounting for 21% loss (Oerke, 2006), and potato late blight is generally recognized as the most important potato disease. While late blight resistance is available, it is frequently not present in popular varieties (Forbes, 2012) so management is often dependent on pesticides, which can be a cost-prohibitive input for resource-poor farmers (Blandon-Diaz *et al.*, 2011, Kromann *et al.*, 2009) and can affect non-target species (Cheatham et al., 2009).

Models of the effect of weather on within-field risk of potato late blight have been evolving for almost a century (Van Everdingen, 1926, Beaumont, 1947), generally drawing on temperature and humidity as the most important predictors (Harrison, 1992). Fry *et al.* created SimCast (1983) and Grünwald *et al.* (2002) further developed the SimCast model and demonstrated that it also performed well in a tropical highland location. The SimCast algorithm estimates the risk of damaging late blight levels, expressed as ‘blight units’, based on the temperature during the consecutive hours in a day when relative humidity is above 90%. SimCast thus uses hourly weather data as input. To rescale SimCast for larger time steps and easier application to wider geographical areas, we developed a metamodel of the relationship between weather (temperature and relative humidity) and late blight risk, based on SimCast output (Sparks *et al.*, 2011). The metamodel $mm_{Monthly}$ uses monthly time-step temperature and relative humidity data to predict disease risk expressed as ‘blight units’.

Hijmans et al. (2000) evaluated contemporary severity of potato late blight indirectly using tactical decision models, Blitecast (Krause *et al.*, 1975) and SimCast (Fry *et al.*, 1983, Grünwald *et al.*, 2002) to predict the need for a prophylactic pesticide application to control late blight in farmers’ fields. These models were then scaled up to estimate the number of pesticide applications necessary to manage late blight globally. To achieve this, they used monthly climate data and a weather generator to temporally downscale the hourly weather data necessary for these models.

The impacts of climate change on potato late blight have been studied in the Midwestern US (Baker et al., 2005) and Finland (Hannukkala et al., 2007, Kaukoranta, 1996), indicating the potential for increased risk. Our goal was to provide the first global analysis of climate change effects on potato late blight. We used $mm_{Monthly}$ to evaluate the effects of climate change emission scenarios and the level of disease resistance on the change in disease risk. Furthermore, using the $\mathrm{mm}_{Monthly}$ metamodel to evaluate risk illustrates the potential of metamodels for rescaling short-term forecasting models for scenario analysis. Results are discussed in the context of important agroecological areas and political boundaries.

Materials and Methods

As an overview, we used gridded historic climate data (for the reference time period) and gridded, future predicted climate data. A crop model was used to estimate potato-growing seasons for each grid cell for reference and future periods. The climate data were then used in the $\mathrm{mm}_{Monthly}$ model (Sparks et al., 2011) to evaluate late blight risk for a three-month potato-growing season for each grid cell. The $\mathrm{mm}_{Monthly}$ model estimates blight units, a measure of the relative risk of damaging levels of potato late blight occurring given an input of monthly temperature and monthly relative humidity (Sparks et al., 2011). Because late blight occurs so widely in potato production systems and the driving factors are the weather conditions, temperature and relative humidity, we assumed that inoculum was not a limiting factor in areas where potato is grown.

We used CRU CL 2.0 grid mean monthly temperature, mean monthly relative humidity and mean monthly precipitation data from New *et al.* (2002) as our reference climate data. These data are at a spatial resolution of 10 arc minutes (344 km^2) covering the time period from 1961 to 1990. Future climate emission scenario data were downloaded from the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data (Meehl *et al.*, 2007), that we statistically downscaled to 10 arc minute resolution. Only data for General Circulation Models (GCM) that provided maximum temperature, minimum temperature, and vapor pressure were selected (Table 1), relative humidity was calculated from these data. Ensemble model averages of the non-weighted means of the GCM outputs for each respective climate scenario were created for mean monthly temperature and mean monthly relative humidity.

The global daily average blight unit accumulation per month was calculated from mean monthly temperature and mean monthly relative humidity using the $\mathrm{mm}_{Monthly}$ metamodel for the 1961-1990 reference climate normal (referenced from here on by the midpoint year as the 1975 time slice), and three future 20-year time slices, (referenced hereafter by the midpoint year of the time slice: 2000-2019 (2010), 2040-2059 (2050) and 2080-2099 (2090). The relative risk of damaging levels of late blight was then averaged using a three-month moving window to provide the average daily blight unit accumulation for 12 three-month time periods representing three-month potato growing seasons.

Optimal potato planting dates were estimated using the ECOCROP model as implemented in the dismo package in R (Hijmans *et al.*, 2012) using mean monthly temperature, mean maximum monthly temperature, mean minimum monthly temperature and mean monthly precipitation data. The first day of the first month of a three month growing season in which planting would produce the highest potato yield for each grid-cell was calculated. Optimal planting dates were generated for the reference climate normal and the ensemble GCM outputs for each of the three respective future time slices. These data were used to estimate late blight risk for what would be a geographic location's most productive potato growing season in the absence of pests and disease.

Total rainfed and irrigated potato production by country (Portmann *et al.*, 2010) was used to remove areas where potato production is currently limited. Several countries were selected for further analysis because they are representative of highland or lowland tropical potato production, areas where potato is an important crop for poverty alleviation and where late blight is difficult to manage because of year-round potato production (Garrett *et al.*, 2009) (Table 4). These countries include Colombia and Ecuador in the Andean highlands (Figure 4); Ethiopia (Figure 5); Rwanda in the Lake Kivu highlands region (Figure 6); Nepal in the Himalayan highlands and Indo-Gangetic Plain (Figure 7), and Indonesia in the South East Asian highlands (Figure 8).

Results

The following examples illustrate the differences on the ground associated with mean daily growing season blight units. The mean daily blight units in Rwanda during the baseline was 2.41 (Table 2), and Rwanda has had consistent problems with late blight management such that pesticides have frequently been necessary for successful management (Forbes, personal observation). In contrast, the mean daily blight units in Egypt during the baseline were 0.41 (Table 2), and late blight has not generally been a major problem in Egyptian potato production (Forbes, personal observation).

Global average late blight units increase initially (2010 time slice) relative to reference climate data under all three emission scenarios examined (Figure 1). For the A2 and A1B scenarios, the global average accumulation falls in 2050 to levels equal to the historic levels and falls farther in the 2090 time slice. Throughout all three time slices examined for GCM outputs, the B1 scenario has the highest global average risk of the three scenarios and coolest global average temperatures. Initially, during the 2010 timeslice, the average blight units accumulated are nearly equal under all scenarios, by 2050 the scenarios begin to exhibit differing levels of accumulation and by the 2090 time slice the average blight unit levels in each climate scenario differ (Figure 1). However, all three scenarios do have a lower average blight risk accumulation by 2090 than the 1975 time slice.

In the original SimCast model, as temperatures rise above 22 C a longer period of high relative humidity (greater than or equal to 90%) is required to register one blight unit (Fry *et al.* 1983, Grünwald *et al.* 2002). In this analysis temperatures increased steadily during the growing seasons when averaged globally across all potato-growing areas (Figure 1), correspondingly the blight unit accumulation decreased with this temperature increase. The minimum increase was 0.9 degrees for the B1 scenario. The A1B scenario temperatures increased more, by 1.2 degrees with the A2 scenario having the greatest increase in temperature across the time period that we examined with an increase of 1.4 degrees. Relative humidity exhibited little change across the time-slices.

For subsequent analyses, we focused only on changes that occur under the A2 scenario. For a susceptible cultivar, global average blight unit value was 1.26 for the historical average and 1.27 for the 2050 time slice.

Many of the areas where potato is grown exhibited little to no change (-0.5 to 0.5 difference) in daily mean blight units during the growing season (Figure 2 and Figure 3). However, blight units increased in parts of East-Central South America, China, Europe and Canada. The Andes and Himalayan Mountains and Sub-Saharan Africa exhibited a mixture of increasing and decreasing blight unit accumulation. Three of the ten countries experiencing the greatest increases in blight units are located in Africa (Table 2).

All of the top potato growing countries exhibited an increase less than or equal to 0.11 blight units per season change (Table 3) with three countries decreasing. With the minimal changes seen in the top producing countries, the effects of resistance are much less pronounced (Table 3) than among the countries most affected (Table 2). Resistant genotypes are effective in reducing blight risk in all countries, such that no country experiences average blight unit accumulation higher than 0.06.

In the countries selected to represent specific agro-ecosystems, for a susceptible cultivar late blight risk increased in Rwanda and Ethiopia; all other regions examined had a slight decrease in the blight unit accumulation at the country level (Table 4). However, the blight unit accumulations shift within the growing areas for each country, which could influence potato production as some areas experience increased late blight severity, and others experience decreased late blight severity.

Discussion

In general, potato late blight risk, as evaluated using the metamodel under IPCC scenarios, will increase in the near future and then begin to decrease (after the middle of the 21st century). However, the predicted effects of climate change are not equal across geographic locations. Not all areas experience an initial increase in late blight risk, even under the higher emission scenarios, A2 and A1B. Although we focused on the higher emission A2 scenario because it is a marker scenario used by the IPCC (2000) and most closely matches current emission levels, results were very similar for all three scenarios examined. The greatest noticeable difference was that the risk under the B1 scenario does not drop off as much in future time slices. The increase and then decrease in late blight risk is most likely due to how the original SimCast model (Fry *et al.* 1983, Grünwald *et al.* 2000) calculates the accumulation of blight units. In the original SimCast model, as temperatures increase from 8-22 degrees C to 23-26 degrees C for a susceptible, more hours of leaf wetness (hours above RH 90%) are required to accumulate one blight unit. In our analysis, all emission scenarios exhibit an increase in average temperature across potato growing regions for their respective growing seasons, and correspondingly the blight unit accumulations decrease with the increase in temperature while relative humidity changes little. The SimCast model also treats temperature effects differently below the 8-12 degrees C range. At cooler hourly temperatures, accumulation of blight units decreases with increased temperature. Thus, one would anticipate increased late blight risk for the very coolest potato growing areas (e.g., the highest parts of the Andes). These areas probably represent small proportions of total potato production in the countries where they occur and may have simply counterbalanced warmer areas, contributing to a small change in risk at the country or regional level over time.

Often there are substantial differences among different GCM model outputs (ref) and individual GCMs tend to have particular areas where they are more accurate and, as Phillips (1984) suggests, there is no one best GCM. Because of this, and because we were interested in the effects of climate change globally, rather than for specific areas, we used an ensemble model approach (Bates *et al.*, 1969) since.

Where potato late blight risk increases, what are the implications for management? Potato late blight is a challenge to manage, particularly for resource-poor farmers who may have limited access to appropriate fungicides (Blandon-Diaz *et al.*, 2011, Kromann *et al.*, 2009), and limited knowledge of late blight management. New, effective fungicide compounds have been released in markets in the industrialized countries but these often do not make it to developing countries, or at least not to the more remote areas. Host plant resistance, shown in this analysis to be an effective way of adapting to changing risk, would appear to be a better strategy for developing country farmers than fungicide use. Nonetheless, development and adoption of resistant cultivars has been slow (Forbes, 2012). Current levels of resistance provide some benefits, and there is the potential for technological advances to increase the level and/or durability of late blight resistance. There is also the potential for advances in the quality and durability of fungicides used for potato late blight management. Other agronomic practices can also contribute to late blight management, including planting dates to avoid conditions that favor late blight (Devaux *et al.*, 1987), use of field sanitation, and crop genotype mixtures in the field (Pilet *et al.*, 2006, Garrett *et al.*, 2001), though the utility of these practices can also depend on environmental conditions (Garrett *et al.*, 2009).

Studies of global risk invariably include a number of assumptions. First, our study focused on risk of late blight in the future at different spatial scales but did not address the suitability of these areas for potato production in the future. It is possible that along with a change in risk of late blight, the suitability for potato production in these areas also changes due to a changing physical or social environment. Second, another aspect of future scenarios that is not addressed by evaluations of average conditions is the potential effect of weather extremes and weather variability (Rosenzweig *et al.*, 2001, Garrett *et al.*, 2013). Climate data represent weather means, but not the typical variation of weather. Late blight risk will likely be affected differently across years as a result of changing weather patterns not represented by climate. Third, this model does not account for an increase in risk as inoculum builds over the growing season - the compound interest principle (Van der Plank, 1963) - it simply evaluates average risk during the three-month growing season determined to be optimal for potato yield. The average risk approach used here can be viewed as a conservative estimate of differences in risk, while 'compound interest' pathogen reproduction across the season may produce larger differences in disease risk between time slices and between areas. Fourth, we assumed that inoculum was not limiting, an assumption that is generally reasonable for potato late blight. However, for more detailed regional analyses it might be important to evaluate whether inoculum might be limiting in particular locations, and how locations may be linked to sources of inoculum (Sutrave *et al.*, 2012). Effects of regional inoculum load or 'risk neighborhoods' could be incorporated in more detailed analyses (Skelsey et al., in review). All else being equal, a location will experience higher late blight risk if its neighbors have higher risk. Spatio-temporal models such as those developed by Skelsey *et al.* (2009) can model regional interactions of inoculum loads. At larger scales in future scenario analyses, the level of confidence in estimates of fine-resolution weather events may not warrant such detailed models evaluation. Finally, our predictions assume no pathogen evolution for the primary driving factors, which in this case are temperature and RH. As noted, the predicted decrease in blight units after 2050 occurs because of the requirement for longer periods of RH at higher temperatures for infection to occur. Pathogen change at the population level for temperature and RH responses has been recorded in the past and even resulted in the reparameterization of a simulation model (_).

The choice of planting date is an important one for disease management, and can be used as an effective tool in controlling late blight (Devaux *et al.*, 1987). Growers may choose to reduce late blight risk by planting in a season that is sub-optimal from the standpoint of potato yield in the absence of disease (Devaux *et al.*, 1987). Such a decision would be another type of cost of potato late blight risk. In other cases, growers may plant potato in other seasons in addition to the optimal season for yield; our analysis does not take into account risk during additional seasons. The discrete nature of monthly data can produce some temporary artifacts over time in our analysis. In some cases, lags in responses to climate change scenarios may occur because of the use of monthly climate data in the ECOCROP model to predict optimal planting dates. A particular time slice might not reach a tipping point where the optimal planting month changes and increases blight risk.

Socio-economic models can also help to inform predictions of future disease risk. Synthesis in a GIS of socio-economic models, crop yield models, and data such as generated by mm$_{Monthly}$ could provide a general picture of the effects of climate change on potato yield in the future. Studies have incorporated crop growth models with socio-economic effects, but apparently have not simultaneously included the effects of climate on plant disease (Wei *et al.*, 2009). Other types of more detailed socio-economic models could incorporate farmers' decision-making about use of fungicides and resistant varieties, where the regularity of disease impact may influence adoption (Lybbert *et al.*, 2010). For example, the adoption of resistant varieties could be surveyed or modeled and then coupled with the outputs from a crop health model such as mm$_{Monthly}$ for an estimate of the potential impact of releasing a resistant crop genotype. Adoption of plant disease management that reduces greenhouse gas emissions per unit product can, itself, be considered a form of climate change mitigation (Mahmuti *et al.*, 2009).

Analyses of future scenarios for potato late blight will continue to improve as models of climate/weather, potato production, and disease all improve. We have discussed some of the areas for improvement in biological and socio-economic models above. Another area for improvement will be the development of coordinated data sets for the global presence of disease (Jeger *et al.*, 2008, Shaw *et al.*, 2011). Even though potato late blight is one of the most intensively studied plant diseases, extensive maps of observed disease severity are not available. This is an even greater problem for less-studied diseases. Without such data sets, ground-truthing of model predictions is limited. Future scenario analyses will also need to be updated as new information about environmental requirements for pathogens becomes available. A dramatic example of a change in environmental tolerance is the global spread of more heat tolerant and aggressive populations of the wheat stripe rust pathogen (Milus *et al.*, 2006, Hovmoller *et al.*, 2011). There is the potential for *P. infestans* to develop a wider range of temperature optima. A greater impact might result if *P. infestans* developed greater tolerance for dry conditions, so that the relative humidity requirements included in current models of late blight could be relaxed. The requirement for high relative humidity, a proxy for leaf surface wetness, is common for many foliar pathogens (Caubel *et al.*, 2012, Huber *et al.*, 1992). The requirement for high relative humidity may limit the response to climate change for other foliar pathogens, which would otherwise have experienced temperature as a primary limiting factor.

Metamodels such as mm$_{Monthly}$ give plant pathologists new tools for the ongoing battle with plant disease. This framework to quickly estimate relative risk globally using readily available weather data is a useful tool because previously producing such estimates was computationally and time intensive. The mm$_{Monthly}$ metamodel can produce localized results in a few minutes and a global estimate for a one month time period at 10 arc-minute resolution in about an hour. These sorts of tools provide outputs that allow us to evaluate possible effects of disease control, shifts in crop establishment date, and changes in climate.

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Table 1. General Circulation Models (GCM) selected, which provided maximum and minimum temperature and relative humidity data for three emission scenarios for use in mm$_{\text{Monthly}}$.

GCM Abbreviation	**GCM Model Name**	**Emission Scenarios**
BCCR BCM2.0	Bjerknes Centre for Climate Research Bergen Climate Model Version 2.0	A1B, A2, B1
CSIRO mk3.0	Commonwealth Scientific and Industrial Research Organization GCM mark 3	A1B, A2, B1
GISS AOM	Goddard Institute for Space Studies Atmosphere-Ocean Model	A1B, B1
INMCM3.0	Institute for Numerical Mathematics Version 3.0	A1B, A2, B1
MIROC3.2 hires	Model for Interdisciplinary Research on Climate	A1B, B1

Table 2. Daily average blight unit accumulation and change during the growing season for the ten potato producing countries experiencing the greatest total increase in blight unit accumulation as predicted by mm_{Monthly} *model using historic climate normal, 1961-1990 (1975 time slice), and 2040-2059 (2050 time slice) A2 climate. Blight units are a predictor of biological risk based on weather and potato genotype resistance.*

	Susceptible Blight Units			**Resistant Blight Units**		
Country	**1975**	**2050**	**Change**	**1975**	**2050**	**Change**
Rwanda	2.41	3.55	1.14	1.43	2.22	0.79
Burundi	2.54	2.97	0.43	1.54	1.82	0.28
Uruguay	1.87	2.30	0.43	1.05	1.32	0.27
Portugal	1.19	1.60	0.41	0.65	0.87	0.22
Iraq	0.58	0.87	0.29	0.28	0.45	0.17
Greece	0.86	1.15	0.29	0.45	0.62	0.17
Israel	0.92	1.20	0.28	0.48	0.64	0.16
New Zealand	2.43	2.70	0.27	1.41	1.60	0.19
Estonia	2.39	2.65	0.26	1.38	1.58	0.20
Egypt	0.41	0.63	0.22	0.21	0.33	0.12

Table 3. Daily average blight unit accumulation and change during the growing season for the top ten potato producing countries by number of hectares planted to potato as predicted by mm_{Monthly} *model using historic climate normal, 1961-1990 (1975 time slice) and 2040-2059 (2050 time slice) A2 climate scenario. Blight units are a predictor of biological risk based on weather and potato genotype resistance.*

Country	**Hectares of Potato**	**Susceptible Genotype Blight Units**			**Resistant Genotype Blight Units**		
		1975	**2050**	**Change**	**1975**	**2050**	**Change**
China	4401727	1.34	1.33	-0.01	0.75	0.75	0.00
Russia	3229000	1.12	1.17	0.05	0.61	0.65	0.04
Ukraine	1600000	1.28	1.30	0.02	0.70	0.71	0.01
India	1410000	0.88	0.96	0.08	0.34	0.38	0.04
Poland	811979	2.17	2.13	-0.04	1.24	1.22	-0.02
Belarus	540000	2.02	1.69	-0.33	1.15	0.94	-0.21
United States	516590	0.88	0.90	0.02	0.48	0.49	0.01
Germany	284078	1.81	1.92	0.11	1.02	1.08	0.06
Peru	271185	1.34	1.35	-0.01	0.66	0.64	-0.02
Romania	270000	1.98	2.04	0.06	1.12	1.15	0.03

Table 4. Mean change in blight units from historic climate normal, 1961-1990 (1975 time slice) to 2040-2059 (2050 time slice) for the A2 climate scenario for select highland or lowland tropical potato production areas where potato is an important crop for poverty alleviation and where late blight is difficult to manage because of year-round potato production. Blight units are a predictor of biological risk based on weather and potato genotypic resistance.

Agroecosystem	**Country**	**Susceptible Genotype Blight Units**			**Resistant Genotype Blight Units**		
		1975	**2050**	**Change**	**1975**	**2050**	**Change**
Andean Highlands	Colombia and Ecuador	2.23	2.20	-0.03	1.03	1.00	-0.03
Ethiopian Highlands	Ethiopia	0.63	0.68	0.05	0.33	0.35	0.02
Lake Kivu Highlands	Rwanda	2.41	3.55	1.14	1.43	2.22	0.79
Indo-Gangetic Plain and Himalayan Highlands	Nepal	1.47	1.45	-0.02	0.85	0.81	-0.02
South East Asia Highlands	Indonesia	1.84	1.78	-0.06	0.75	0.69	-0.06

Figure 1: Average yearly global blight unit accumulation during the growing season for four time slices for four time slices: 1961-1990, 1975 time slice; 2000-2020, 2010 time slice; 2040-2060, 2050 time slice; and 2080-2100, 2090 time slice, for three IPCC emission scenarios: A2; A1B; and B1. Blight units are a measure of the biological risk of damaging levels of late blight of potato developing due to favorable weather conditions and are derived from the SimCast model.

Figure 2: Average yearly global potato growing seasons' and regions' temperatures for four time slices: 1961-1990, 1975 time slice; 2000-2020, 2010 time slice; 2040-2060, 2050 time slice; and 2080-2100, 2090 time slice, for three IPCC emission scenarios: A2; A1B; and B1.

Figure 3: The change in global potato late blight relative risk as predicted by $mm_{Monthly}$ model using historical climate normal, 1961-1990 (1975 time slice) and 2040-2059 (2050 time slice) A2 climate scenario for a **susceptible** potato genotype. Blight units are a predictor of biological risk based on weather and potato genotypic resistance. Areas of highest increased risk appear in dark red, areas of greatest decreased risk appear in dark blue and grey indicates limited potato production.

Figure 4: The change in global potato late blight relative risk as predicted by $mm_{Monthly}$ model using historic climate normal, 1961-1990 (1975 time slice) and 2040-2059 (2050 time slice) A2 climate scenario for a **resistant** potato genotype. Blight units are a predictor of biological risk based on weather and potato genotypic resistance. Areas of highest increased risk appear in dark red, areas of greatest decreased risk appear in dark blue and grey indicates limited potato production.

Figure 5: The change in potato late blight relative risk for the Andean Highlands of Colombia and Ecuador as predicted by $mm_{Monthly}$ model using historic climate normal, 1961-1990 (1975 time slice) and 2040-2059 (2050 time slice) A2 climate scenario for a **susceptible** potato genotype. Blight units are a predictor of biological risk based on weather and potato genotypic resistance. Areas of highest increased risk appear in dark red, areas of greatest decreased risk appear in dark blue and grey indicates limited potato.

Figure 6: The change in potato late blight relative risk for the Ethiopian Highlands as predicted by $mm_{Monthly}$ model using historic climate normal, 1961-1990 (1975 time slice) and 2040-2059 (2050 time slice) A2 climate scenario for a **susceptible** potato genotype. Blight units are a predictor of biological risk based on weather and potato genotypic resistance. Areas of highest increased risk appear in dark red, areas of greatest decreased risk appear in dark blue and grey indicates limited potato production.

Figure 7: The change in potato late blight relative risk for the Lake Kivu highlands region and Rwanda as predicted by $mm_{Monthly}$ model using historic climate normal, 1961-1990 (1975 time slice) and 2040-2059 (2050 time slice) A2 climate scenario for a **susceptible** potato genotype. Blight units are a predictor of biological risk based on weather and potato genotypic resistance. Areas of highest increased risk appear in dark red, areas of greatest decreased risk appear in dark blue and grey indicates limited potato production.

Figure 8: The change in potato late blight relative risk for the Indo-Gangetic Plain and

Himalayan Highlands in Nepal as predicted by $mm_{Monthly}$ model using historic climate normal, 1961-1990 (1975 time slice) and 2040-2059 (2050 time slice) A2 climate scenario for a **susceptible** potato genotype. Blight units are a predictor of biological risk based on weather and potato genotypic resistance. Areas of highest increased risk appear in dark red, areas of greatest decreased risk appear in dark blue and grey indicates limited potato production.

Figure 9: The change in potato late blight relative risk for the South East Asian Highlands in Indonesia as predicted by $mm_{Monthly}$ model using historic climate normal, 1961-1990 (1975 time slice) and 2040-2059 (2050 time slice) A2 climate scenario for a **susceptible** potato genotype. Blight units are a predictor of biological risk based on weather and potato genotypic resistance. Areas of highest increased risk appear in dark red, areas of greatest decreased risk appear in dark blue, grey indicates limited potato production.