Eur J Plant Pathol
DOI 10.1007/s10658-016-1076-6

A climatic risk analysis of the threat posed by the South American leaf blight (SALB) pathogen *Microcyclus ulei* to major rubber producing countries

C. Bindu Roy · Zoe-Joy Newby · Jacob Mathew · David Ian Guest

Accepted: 19 October 2016

Abstract South American leaf blight (SALB) of the Pará rubber tree, *Hevea brasiliensis* Muell. Arg., caused by the plant pathogenic fungus *Microcyclus ulei* (Henn.) Arx, is recognized as the most serious threat to the natural-rubber industry worldwide. While the pathogen is currently restricted to South America, the warm humid climatic conditions in Asia and Africa, which contribute to over 97 % of world's natural rubber production are similar to the South American tropics, indicating a significant threat to global rubber production, should the pathogen be introduced to these regions. The present study aims to assess climate suitability for the occurrence of *M. ulei* in different parts of the world, based on the available literature for *M. ulei* pathogen establishment, including temperature, relative humidity and precipitation. The risk analysis study provides a preliminary indication of the likely threat of *M. ulei* in different rubber growing areas of the world and highlights the need for more information on pathogen biology, diversity and environmental tolerance.

Key words *Hevea brasiliensis* · *Microcyclus ulei* · SALB, South American leaf blight

C. B. Roy (✉) · J. Mathew
Plant Pathology Division, Rubber Research Institute of India, Kottayam, India
e-mail: binduroy@rubberboard.org.in

Z.-J. Newby · D. I. Guest
Faculty of Agriculture and Environment, The University of Sydney, Sydney, NSW, Australia

Introduction

More than 12 million tonnes of natural rubber were produced globally in 2014 with demand outstripping supply (IRSG 2015). Natural rubber, which is derived from latex of Pará rubber tree, *Hevea brasiliensis* Muell. Arg., which is native to Brazil, is a major economic crop in many countries. South American leaf blight (SALB), caused by the Ascomycete fungus *Microcyclus ulei* (Henn.) Arx (Ascomycota, Dothideomycetes), is a major factor limiting the cultivation of rubber in South and Central America. SALB is a serious threat to the natural rubber industry throughout the world (van Beilen and Poirier 2007), including Asia and Africa where 97 % of commercial rubber production is located (IRSG 2014; Chee et al. 1985). In the early twentieth century epidemics of SALB led to failure of rubber cultivation in tropical America (Grandin 2009) and as a result of its potential serious economic consequence, stringent quarantine measures, especially for importation of budwood material, were adopted to exclude SALB from Asia (FAO 2007; Lieberei 2007).

The fungus was first observed in 1900 in the Amazon rainforest in Peru and Brazil (Hennings 1904). Immature leaf, stem and fruit tissues of *Hevea brasiliensis*, *H. benthamiana*, *H. spruceana*, *H. guianensis* and *H. camporum* are vulnerable to the disease (Chee and Holliday 1986). Leaves are most susceptible to infection when they are less than 12 days old (Invasive Species Compendium 2009). Therefore, new plantings of trees 3–4 years old that produce new flushes throughout the year are at greatest risk as there is continuous succession

Published online: 02 November 2016

Table 1 Membership conditions for environmental parameters included in SALB risk model

Parameter	Non membership range	Membership range
Temperature (°C)	Minimum - 18.49; 36.5 - maximum	18.5–36.49
Relative humidity (%)	Minimum - 64.9	65 - maximum
Monthly precipitation (mm)	Minimum - 62.9	63 - maximum

of new leaves. Mature trees on the contrary, undergo seasonal defoliation, and are at greatest risk of disease in the month following refoliation.

Weather conditions are known to influence SALB severity (Gasparotto et al. 1989a; Guyot et al. 2010), with relative humidity (RH) and temperature the key drivers of disease. Gasparotto et al. (1989a) reported that disease severity also differs with the time of year, and compared three different disease outbreaks in Viana (Espirito Santo, Brazil), characterised by different RH and temperature conditions. Thus, it is clear that interaction between climatic variables and pathogen availability need to be considered to explain disease dynamics. Climatic conditions not only influence the expression of disease but also pathogen growth and reproduction. Germination of spores, growth and sporulation of the fungus are favoured at temperatures between 24 and 28 °C (Holliday 1970; Chee 1976; Gasparotto et al. 1989b). In the field, infection requires long wet periods (Chee et al. 1985). Temperatures lower than 20 °C have been reported to have a negative effect on disease development, while high relative humidity (RH) (number of days with wetness duration >90 % for 6 h consecutively) and longer wet periods (number of days with wetness duration >6 h consecutively) are highly correlated with disease development (De Camargo et al. 1967; Gasparotto 1988; Gasparotto et al. 1989b). Guyot et al. (2010) observed that while long periods of high RH favoured infection of young leaves, once the disease was present, climatic conditions were not limiting for the development of disease symptoms. However, it is worth noting that much of the published information is more than 40 years old, making

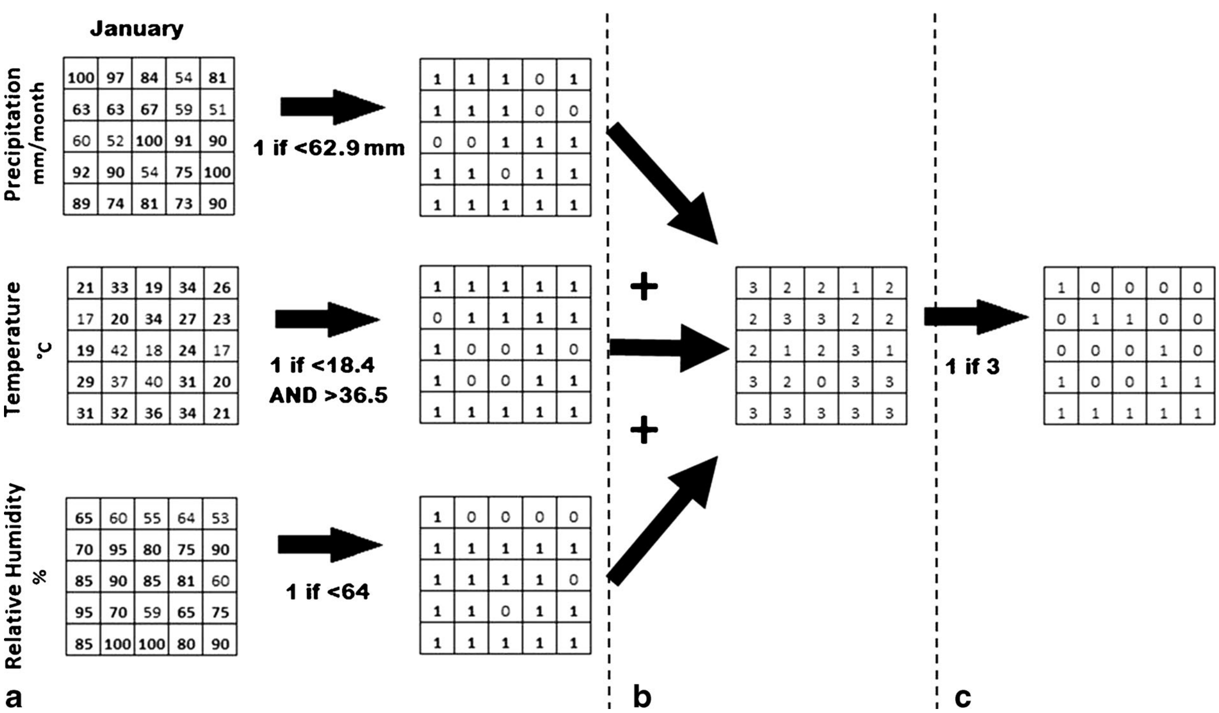

Fig. 1 *Microcyclus ulei* distribution model construction process. For each month, raster layers of averaged climatic variables were coded such that conducive cells had a value of 1 **a**. The three binary maps were then added together to produce a single raster with values 0–3 **b**. From this raster, all cells were given a value of 0 except those cells where all three variables were conducive (cell value =3), in which case they were recorded to a value of 1 and represented cells predicted to be conducive to *M. ulei* in that particular month **c**

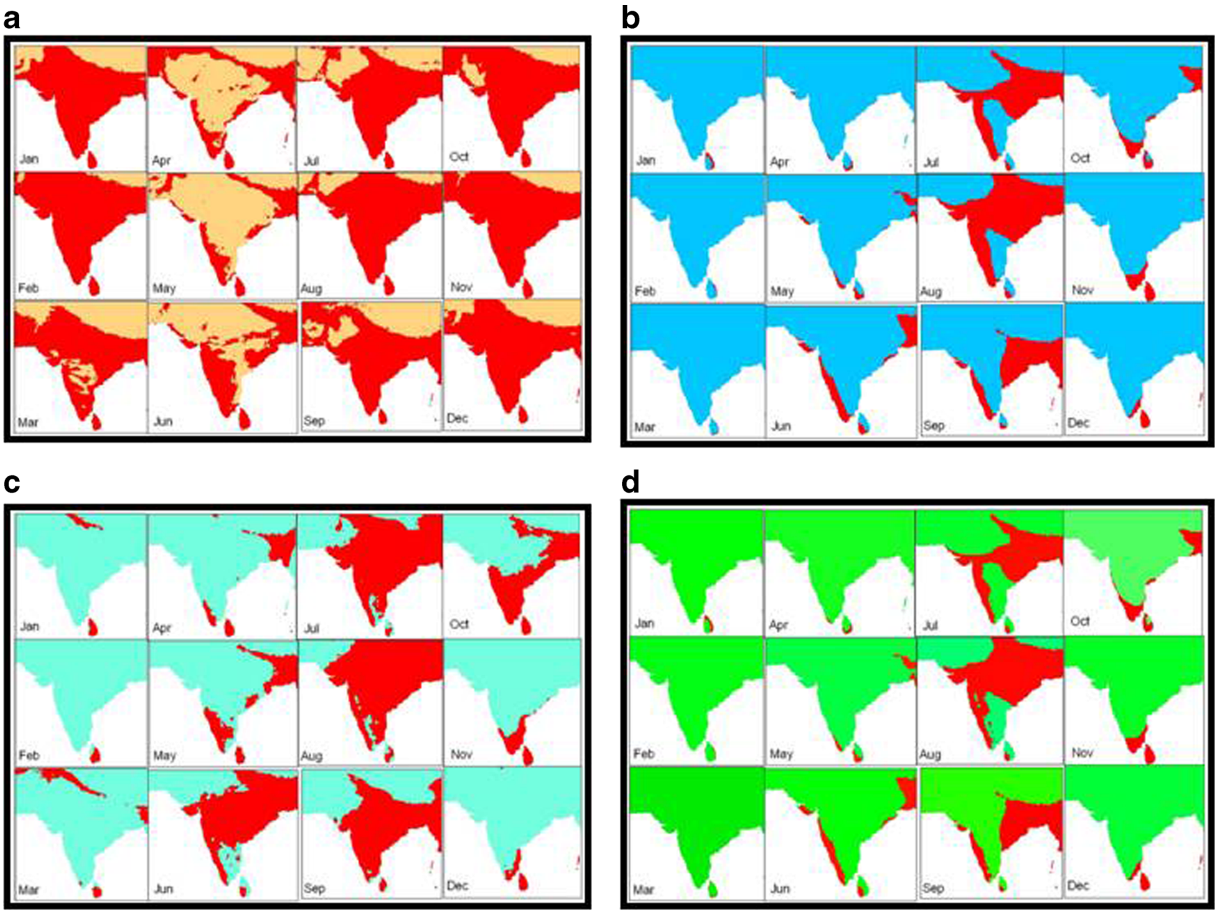

Fig. 2 a-d. Regions of India predicted to be climatically suitable to the establishment of *M. ulei.* Predictions were based on the distribution of conducive temperature **a**; relative humidity **b**; precipitation **c** and by merging all these three factors together **d** for India. The *red shaded* regions are potential regions for SALB disease incidence

interpretations of disease under current climatic conditions, and within new areas, difficult.

A means by which this difficulty can begin to be overcome includes the development of species distribution models (SDM), whereby the potential spread or occurrence of an introduced pathogen can be estimated (Elith and Leathwick 2009). SDMs are used extensively to study the potential distribution and impacts of introduced species and disease in management efforts in natural and altered ecosystems (Alexander 2010; Meentemeyer et al. 2012; Plantegenest et al. 2007; Yuen and Mila 2015).

A preliminary risk analysis by Lin (FAO 2007) used annual average temperature data in March, April and May (refoliation in Northern Hemisphere); annual average temperature data in September, October and November (refoliation in Southern Hemisphere), which were higher than 18.5 °C; annual rainfall greater than 760 mm and no more than six consecutive months with less than 42 mm per month of rainfall to identify Thailand, Indonesia and Malaysia as areas with suitable climates for SALB. The present study aims to use ArcMap, the main component of Esri's ArcGIS suite of geospatial processing programs to assess climate suitability for the occurrence of *M. ulei* in different parts of the world, and to identify risk zones in these rubber growing regions.

Methods

The potential distribution of *M. ulei* in different rubber growing regions of the world was predicted using a rule-based approach. Such models can be utilised in

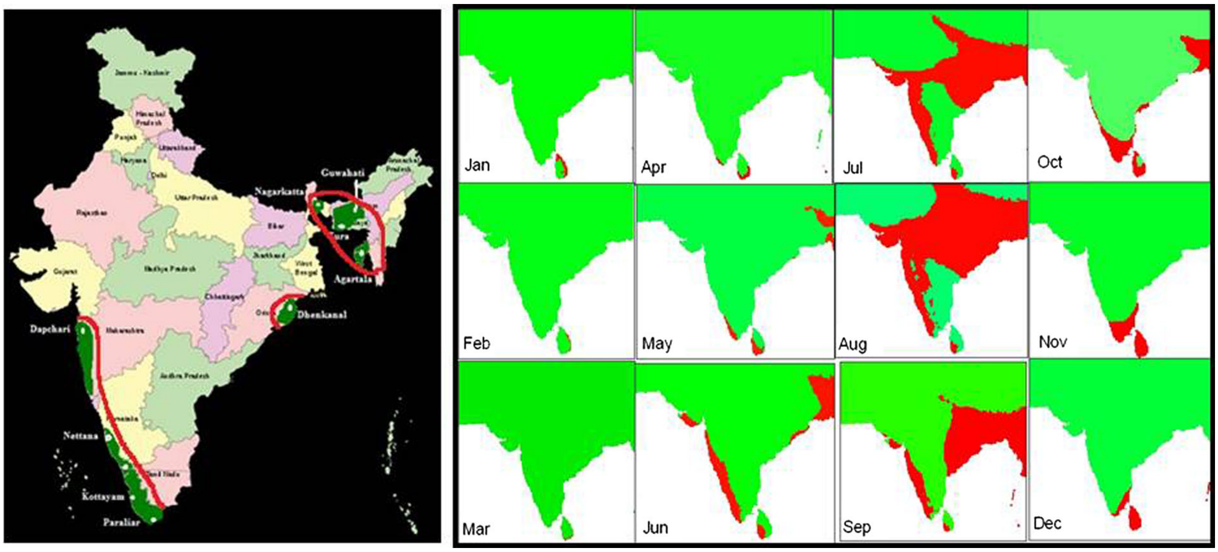

Fig. 3 Map of India showing rubber growing tracts (both traditional and non-traditional) and climate suitability model developed for the country. The *red shaded* regions are potential regions for *M. ulei* establishment

circumstances where there is limited information on an organism's distribution (Guisan and Zimmermann 2000). Such is the case here, as *M. ulei* is currently only known to occur in a few countries, and is not known to be present outside South America. A rule-based approach is also particularly suitable as the resulting model can be dynamically adjusted as our understanding of species biology changes (Guisan and Thuiller 2005; Barry and Elith 2006). More specifically, the model utilises an 'environmental envelop' approach, as particular environmental variables have been used to identify suitable habitats.

Given the influence of temperature, rainfall and relative humidly on the occurrence of *M. ulei* (Chee 1976;

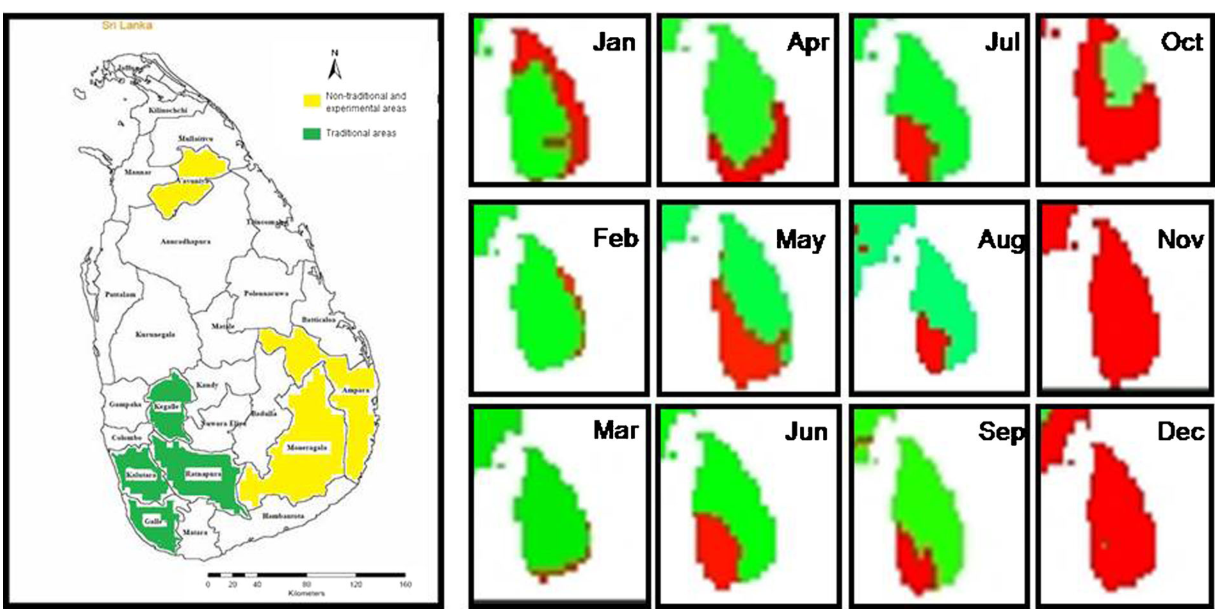

Fig. 4 Map of Sri Lanka showing rubber growing tracts (both traditional and non-traditional) and climate suitability model developed for the country. The red shaded regions are potential regions for *M. ulei* establishment

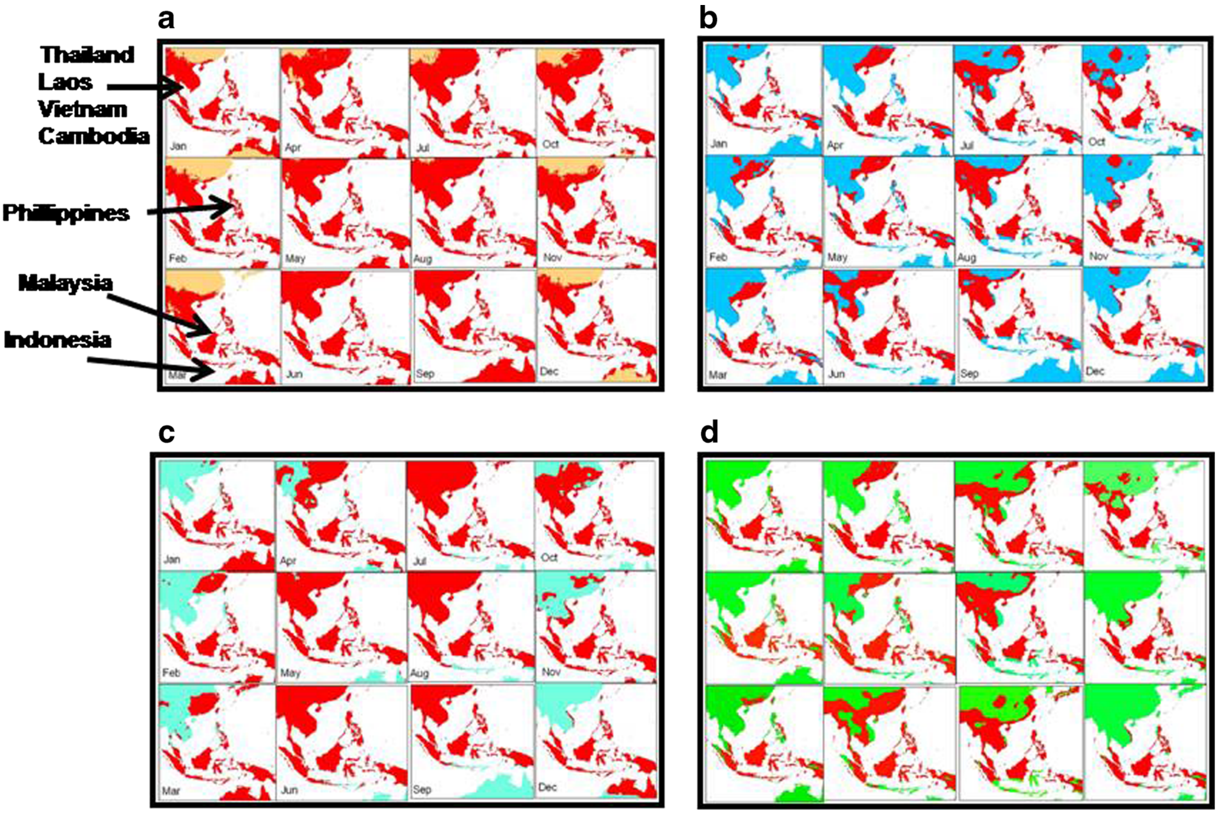

Fig. 5 a-d. Climate suitability for development of SALB disease assessed individually based on temperature **a**; relative humidity **b**; precipitation **c** and by merging all these three factors together **d** for South East Asia. The *red shaded* regions are potential regions for *M. ulei* establishment

FAO 2007; Gasparotto et al. 1989b; Guyot et al. 2010; Holliday 1970), global datasets were used for the development of a model using temperature, rainfall and relative humidity as predictor variables to identify areas climatically suitable for the pathogen. Additionally, as younger plants produce multiple susceptible flushes throughout the year, models were constructed for each month.

Global climate surfaces were obtained from the WorldClim website (www.worldclim.org). The CliMond datasets (Kriticos et al. 2012) utilised here represent monthly means of climatic variables accumulated from weather station data averages for the period 1961 to 1990. Layers for mean monthly precipitation, relative humidity and maximum temperature of the coldest period were downloaded from WorldClim as grid (raster) files with a 10 min resolution (18.6 × 18.6 km^2 at the equator). Layers for each variable for each month were imported into ArcMap 9.3. Using the raster calculator, Boolean operators were used to recode the value of each cell to either suitable (with a value of one) or unsuitable (with a value of zero) (Table 1). For example, if the total precipitation of a cell was below 62.9 mm, then that cell was defined as unsuitable and assigned a value of zero. The three Boolean layers for each month were then summed using the raster calculator, producing maps for each month with a range of values from 0 to 3. The final model (for each month) was then produced using the raster calculator to define cells with a value of 3 as suitable, while all other cells (values 0–2), were considered unsuitable. As such, a cell was only considered suitable for *M. ulei*, if precipitation, relative humidly and temperature were all conducive. The model construction process has been demonstrated in Fig. 1.

Results and discussion

The occurrence of any disease requires a virulent pathogen, susceptible host tissues and a favourable environment. We have developed a pathogen distribution model

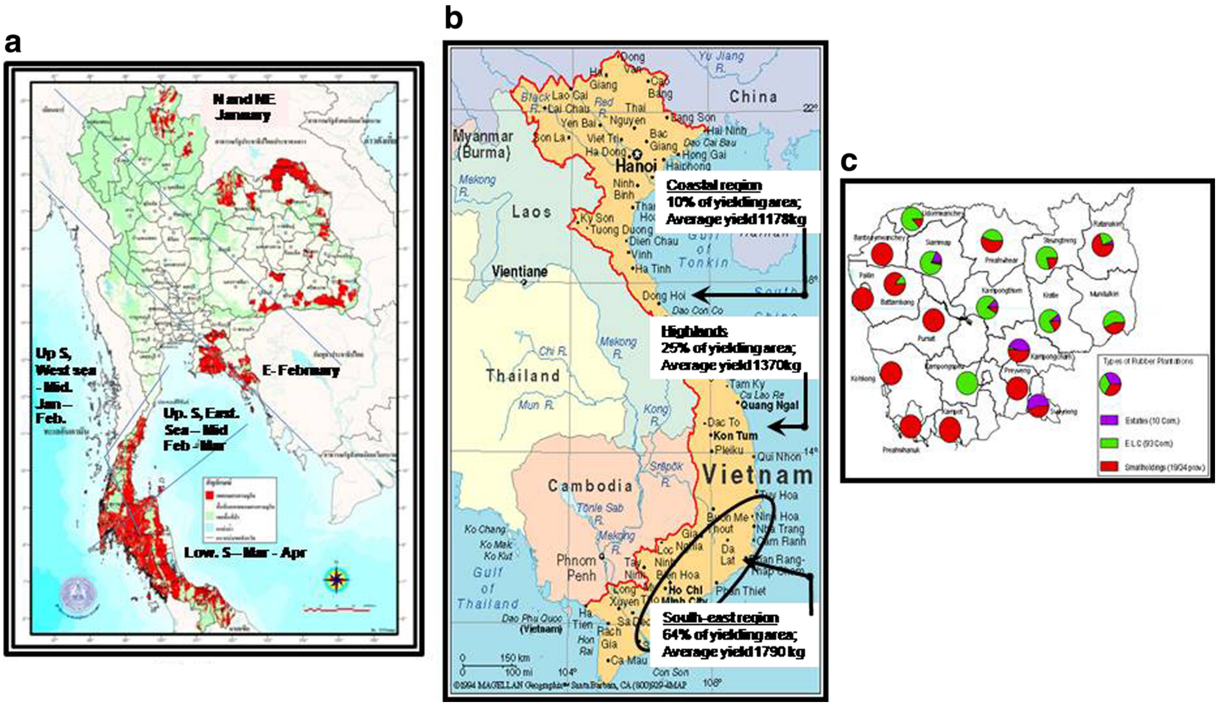

Fig. 6 Map of Thailand **a**, Vietnam **b** and Cambodia **c** showing rubber growing tracts

indicating that there are many regions which have potentially conducive conditions to *M. ulei* for many months of the year. However, the risk model also reveals that even if the pathogen was introduced to countries outside of South America, SALB may not establish in many rubber-growing areas because one or more climatic requirements are not met during the cooler and drier months of the year when refoliation occurs and mature plants are most susceptible to infection.

The model indicates that SALB infection poses a low risk to rubber in India (Figs. 2d and 3) because relative humidity (Fig. 2b) and precipitation (Fig. 2c) are not suitable to *M. ulei* during the refoliation period (December to February). However, younger plants may be susceptible to infection in some regions if their refoliation coincides with climatically conducive conditions which may also result in them becoming reservoirs of pathogen inoculum.

Although most of Sri Lanka was not identified at risk of infection during refoliation (January to April), data for the rubber growing areas of Ampara and Moneragala suggests that the climate is suitable for *M. ulei* infection, and therefore these regions are at risk of SALB establishment during conducive periods (Figs. 2d and 4). In South East Asian rubber growing areas refoliation commences from January and sometimes continues until April.

Our modeling suggests that parts of Malaysia, Philippines and Indonesia have average climatic conditions that are favorable for SALB during the refoliation period of mature plants (April to May) (Fig. 5d), which is a matter of concern for these regions (FAO 2007). However, unlike this earlier prediction, our model suggests that mature *H. brasiliensis* in much of Thailand (Figs. 5d and Fig. 6a), Vietnam (Fig. 6b), Cambodia (Fig. 6c) and Laos are at lower risk from the threat of SALB, because climatic conditions are, on average, not conducive to *M. ulei* during refoliation. In China, rubber is cultivated in Yunnan and Hainan (Fig. 7). Although temperature and relative humidity are suitable, precipitation in these regions is, on average, insufficient and therefore, both these regions are at lower risk of *M. ulei* occurrence and therefore SALB.

In Africa, refoliation occurs from February to March when average temperatures are suitable for *M. ulei* infection in all rubber growing regions (Fig. 8). However, both relative humidity and precipitation are, on average, suitable during the refoliation period only in parts of Gabon, Congo, Zambia and Malawi, and these regions would be at risk of SALB establishment if *M. ulei* was

Fig. 7 Map of China showing rubber growing regions

introduced (Fig. 8). Again, younger plants may be at greater risk in a number of regions as the climate is conducive to *M. ulei*, in the second half of the year.

Although models of the potential of *M. ulei* infection have already been published (FAO 2007; Guyot et al. 2010), we have produced a global, monthly model with the results expressed as a visual geographically referenced product. This makes it particularly easy for growers, land managers and researchers to easily identify a region of interest, and determine if and when they may incur problems with SALB if *M. ulei* was introduced. Models of potential pathogen distribution are routinely constructed using climatic conditions within the context of a GIS-interface (Alexander 2010; Plantegenest et al. 2007). For example, the distribution of *Phaeocryptopus gaeumannii*, the causal agent of Swiss Needle Cast, has been modelled for the state of Oregon in the USA with an R-squared value of 0.8 (Manter et al. 2005) indicating a reasonable level of accuracy. Suitable habitats for the distribution of disease vectors of West Nile Virus in Tennessee have also been modelled (Ozdenerol et al. 2008), allowing land managers to apply appropriate pest control measure. More recently, a model of the potential distribution of *Phytophthora ramorum* in Europe and the United States of America, was developed for the world, and highlighted many suitable countries where the pathogen is not currently known to occur (Ireland et al. 2013).

Each of these models has been developed using climatic factors. Such models only provide a 'snapshot' of what is happening at that time (Meentemeyer et al. 2012), and are 'risky' (Elith and Leathwick 2009) due to their assumptions and errors (Jeschke and Strayer 2008; Phillips et al. 2006; Vaclavik et al. 2010). As such, basic climatic models should feed into more detailed studies (Manter et al. 2005) and model testing should be performed if distribution data becomes available (Elith and Leathwick 2009; Jeschke and Strayer 2008; Plantegenest et al. 2007). Simple improvements to the accuracy of our model

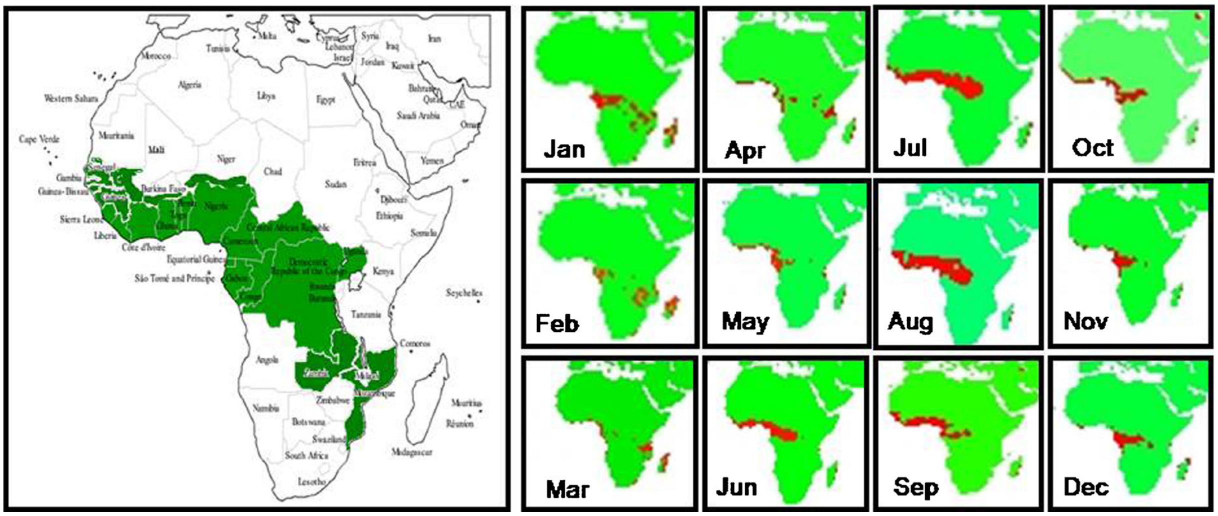

Fig. 8 Map of Africa showing rubber growing tracts along with climate suitability developed for the country. The *red shaded* regions are potential regions for *M. ulei* establishment

could include variable weighting, as was used for predictions of the distribution of *P. ramorum* (Meentemeyer et al. 2004; Vaclavik et al. 2010), however the 'expert-opinion' required for such an approach is currently lacking in the case of *M. ulei*. None the less, our model, although simple, demonstrates the potential for pathogen establishment (Jeschke and Strayer 2008), provides a base-line from which more sophisticated models can be developed (Manter et al. 2005), and can begin to inform management discussions such as planting time, cultivar selection or chemical application (Plantegenest et al. 2007).

The model presented should be considered a preliminary investigation only and the following precautions should be considered. Firstly, we have used data of climatic averages which have been generated from climate models. Any variation to a regions climate (be it an anomaly or longer-term climate change) has the potential to alter the distribution of *M. ulei*.

Secondly, although we have considered the consequence of disease during the refoliation period of mature trees, immature trees (less than 3–4 years old) have multiple refoliation periods throughout the year, and as such the risk of SALB occurring in younger plants is a lot broader than for mature trees. It is not uncommon that immature plants may experience disease that mature plants of the same species do not, a phenomenon known as age-related resistance (reviewed in Palmer and Jones 2002), which may also occur as a consequence of other developmental processes or senescence. Therefore, plant age should be taken into account when considering the suitability of an area for the establishment of *Hevea* plantations.

Thirdly with the exception of India, most rubber growing countries of the world have regions that our modeling predicts are climatically suitable for the establishment of *M. ulei*. However, while our predictions are based on the information available, many references were anecdotal and sometimes contradictory.

Fourthly, the rules applied here are static and carry no temporal component, when in reality the timing and duration of environmental conditions has the potential to influence the pathogens distribution. For example Chee (1976) identified that spores of *M. ulei* only remain viable for between 9 and 12 days on leaves in ambient conditions, while Guyot et al. (2010) identified that the duration of leaf wetness was significantly correlated with disease severity. The interaction between climatic variables and disease occurrence and severity are inevitably complex and require further investigation.

Finally, information on the susceptibility of common genotypes is limited while, changes in pathogen virulence following any incursion could increase the threat SALB poses for the major rubber producing regions of the world (Callaghan and Guest 2015; Chee et al. 1986). Genotype selection as well as strict biosecurity protocols should be implemented to prevent pathogen entry and mitigate disease outbreaks (FAO 2007). We have built a simple rule based model of the distribution of

M. ulei to start to investigate its potential global distribution. As our understanding of the interactions between *H. brasiliensis*, *M. ulei* and climatic conditions improves, the model can be rebuilt accordingly, improving our ability to prevent and control this pathogen as well as SALB.

Acknowledgments The funding of the Australian government by AusAID under the Australian Leadership Award Fellowship program to C. Bindu Roy is gratefully acknowledged.

References

Alexander, H. (2010). Disease in natural plant populations, communities, and ecosystems: insights into ecological and evolutionary processes. *Plant Disease, 94*, 492–503.

Barry, S., & Elith, J. (2006). Error and uncertainty in habitat models. *Journal of Applied Ecology, 43*, 413–423.

Callaghan, S., & Guest, D. I. (2015). Globalisation, the founder effect, hybrid *Phytophthora* species and rapid evolution: new headaches for biosecurity. *Australasian Plant Pathology, 44*, 255–262.

Chee, K. H. (1976). Factors affecting discharge, germination and viability of spores of *Microcyclus ulei*. *Transactions of the British Mycological Society, 66*, 499–504.

Chee, K.H. & Holliday, P. (1986). South American leaf blight of *Hevea* rubber. Malaysian Rubber Research and Development Board, Malaysian Rubber Research and Development Board Monograph No. 13: 50.

Chee, K. H., Darmono, T. W., Zhang, K. M., & Lieberei, R. (1985). Leaf development and spore production and germination after infection of *Hevea* leaves by *Microcyclus ulei*. *Journal of the Rubber Research Institute of Malaysia, 33*(3), 124–127.

Chee, K. H., Zhang, K. M., & Darmono, T. W. (1986). The occurrence of eight races of *M. ulei* of *Hevea* rubber in Brazil. *Transactions of the British Mycological Society, 87*, 15–21.

De Camargo, A. P., Cardoso, R. M. G., & Schmidt, N. C. (1967). Comportamento e ecologia do "mal-das-folhas" daseringueiranas condiçoesclimaticas do planalto Paulista. *Bragantia, 26*(1), 1–8.

Elith, J., & Leathwick, J. R. (2009). Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics, 40*, 677–697.

FAO (2007). Pest risk analysis for South American leaf blight (SALB) of rubber (*Hevea*). http://www.fao.org/docrep/010/ai003e/AI003E25.htm. Accessed 13 Nov 15.

Gasparotto, L. (1988). Epidemiologia do mal das folhas (*Microcyclus ulei* (P. Hem) v. Arx) da seringueira (*Hevea* spp.). Ph.D. thesis, Universidade Federal, Viçosa (Minas Gerais, Brasil), 124 pp.

Gasparotto, L., Zambolim, L., Ribeiro do Vale, F. X., Maffia, L. A., & Junqueira, N. T. V. (1989a). Epidemiologiadomal das folhas da seringueira. *I. Ponte nova-MG. Fitopatologia Brasileira, 14*(1), 65–70.

Gasparotto, L., Zambolim, L., Maffia, L. A., Ribeiro do Vale, F. X., & Junqueira, N. T. V. (1989b). Efeito da temperaturaeumidadesobreainfecçaõ de Seringueira (*Hevea* spp.) por *Microcyclus ulei*. *Fitopatologia Brasileira, 14*(1), 38–41.

Grandin, G. (2009). *Fordlandia: the rise and fall of Henry Ford's forgotten jungle city*. New York: Metropolitan Books.

Guisan, A., & Thuiller, W. (2005). Predicting species distribution: offering more than simple habitat models. *Ecology Letters, 8*, 993–1009.

Guisan, A., & Zimmermann, N. E. (2000). Predictive habitat distribution models in ecology. *Ecological Modelling, 135*, 147–186.

Guyot, J. G., Condina, V., Doaré, F., Cilas, C., & Sache, I. (2010). Segmentation applied to weather-disease relationships in south American leaf blight of the rubber tree. *European Journal of Plant Pathology, 126*, 349–362.

Hennings, P. (1904). Uber die auf *Hevea*–artenbisherbeobachtetenparasitischenpilze. *Notizbl. Bot. Gart. Mus. Berl., 4*, 133–139.

Holliday, P. (1970). South American leaf blight (*Microcyclus ulei*) of *Hevea brasiliensis*. Commonwealth mycological institute. *Phytopathology Papers, 12*, 1–31.

Invasive Species Compendium (2009). *Microcyclus ulei* (South American leaf blight of rubber). http://www.cabi.org/isc/datasheet/33893. Accessed 23 Nov 15.

Ireland, K. B., Hardy, G. E. S., & Kriticos, D. J. (2013). Combining inferential and deductive approaches to estimate the potential geographic range of the invasive plant pathogen, *Phytophthora ramorum*. *PloS One, 8*(5), e63508. doi:10.1371/journal.pone.0063508.

IRSG. (2014). International Rubber Statistical Group. Rubber statistical bulletin. Retrived on July 5, 2014 from http://www.rubberstudygroup.com/publications.aspx.

IRSG (2015). Statistical summary of world rubber situation. http://www.rubberstudy.com/documents/WebSiteData_Aug2015.pdf. Accessed 13 Nov 15.

Jeschke, J. M., & Strayer, D. L. (2008). Usefulness of bioclimatic models for studying climate change and invasive species. *Annual New York Academy of Science, 1134*, 1–24.

Kriticos, D. J., Webber, B. L., Leriche, A., Ota, N., Macadam, I., Bathols, J., & Scott, J. K. (2012). CliMond: global high resolution historical and future scenario climate surfaces for bioclimatic modelling. *Methods in Ecology and Evolution, 3*, 53–64.

Lieberei, R. (2007). South American leaf blight of the rubber tree (*Hevea* spp.): new steps in plant domestication using physiological features and molecular markers. *Annals of Botany, 100*, 1–18.

Manter, D. K., Reeser, P. W., & Stone, J. K. (2005). A climate-based model for predicting geographic variation in Swiss needle cast severity in the Oregon coast range. *Phytopathology, 95*, 1256–1265.

Meentemeyer, R., Rizzo, D., Mark, W., & Lotz, E. (2004). Mapping the risk of establishment and spread of sudden oak death in California. *Forest Ecology and Management, 200*, 195–214.

Meentemeyer, R. K., Haas, S. E., & Vaclavik, T. (2012). Landscape epidemiology of emerging infectious diseases in natural and human-altered ecosystems. *Annual Review of Phytopathology, 50*, 379–402.

Ozdenerol, E., Bialkowska-Jelinska, E., & Taff, G. N. (2008). Locating suitable habitats for West Nile virus-infected mosquitoes through association of environmental characteristics with infected mosquito locations: a case study in Shelby County, Tennessee. *International Journal of Health Geography, 29*, 7–12.

Palmer, S. N., & Jones, D. A. (2002). Age-related resistance to plant pathogens. *Advances in Botanical Research, 38*, 251–280.

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modelling of species geographic distributions. *Ecological Modelling, 190*, 231–259.

Plantegenest, M., Le May, C., & Fabre, F. (2007). Landscape epidemiology of plant diseases. *Journal of the Royal Society, Interface, 4*, 963–972.

Vaclavik, T., Kanaskie, A., Hansen, E. M., Ohmann, J. L., & Meentemeyer, R. K. (2010). Predicting potential and actual distribution of sudden oak death in Oregon: prioritizing landscape contexts for early detection and eradication of disease outbreaks. *Forest Ecology and Management, 260*, 1026–1035.

van Beilen, J. B., & Poirier, Y. (2007). Establishment of new crops for the production of natural rubber. *Trends in Biotechnology, 25*, 522–529.

Yuen, J., & Mila, A. (2015). Landscape-scale disease risk quantification and prediction. *Annual Review of Phytopathology, 53*, 471–481.