Grower perceptions of biotic and abiotic risks of potato production in South Africa

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Abstract

Growers' surveys took place in all sixteen potato growing regions of South Africa in 2013 and 2014. The agro-ecological climate of these regions is diverse and potato is produced in rainy or dry seasons, in winter or summer seasons, or year round. Growers were asked how often in ten years crops suffered more than 25% yield losses due to extreme weather events related to precipitation events such as hail, floods and droughts, and to temperature-related events such as frost and heat waves. Simultaneously they were asked their opinion about occurrence and severity of diseases caused by potato viruses, fungi and bacteria and pests such as nematodes, tuber moths, aphids and leaf miners. Weather related hazards resulted in losses over 25% virtually each year in the Gauteng growing region due to hail, frosts and floods; losses occurred less than once every five years, for example due to extremely high temperatures, in the Sandveld area where growers take a risk by producing potatoes in hot summers. Regarding the biotic factors, every pest or pathogen assessed was reported to occur on at least one farm in each growing region. Countrywide the lowest frequency of 50% was recorded for powdery scab whereas the insects tuber moths, leaf miners and aphids were reported most frequently, by between 88% and 98% of the growers. The complex of silver scurf and black dot resulted in the greatest yield losses in all growing regions, followed closely by tuber moth, early blight and the blackleg / soft rot disease complex. Yield losses due to potato virus Y, potato leaf roll virus and aphids were not reported as being very severe. When the growers' perceptions of severity of biotic factors were accumulated, significant differences between the regions appeared, with the Eastern Cape most prone with an accumulated score of 700 due to an array of pests and diseases, and the North-West with a score of only 50 mainly attributed to root knot nematodes. Growers were also asked how frequently biocides were applied to potato to control soil-borne organisms (nematicide and seed treatment), foliar fungi or insects. There were no significant correlations between frequency of biocide applications and severity of the disease as reflected in yield losses, most likely because growers use biocide applications as insurance against pests and diseases. This is common among crop farmers around the world. Although potato production in South Africa appears to carry more risks than production elsewhere, South African commercial potato growers are economically competitive when compared to growers in other areas of the globe, with comparable planting conditions and risks.

Keywords: Potatoes; South Africa; Pests; Pathogens; Climate change; Abiotic risks; Grower Knowledge; Technology Transfer

1. Introduction

In South Africa potatoes are produced in 16 distinct regions (Figure 1), differing in soils and climatic conditions. The regions also have different planting times throughout the year, resulting in four main agro-ecological seasons (Haverkort *et al.*, 2013), namely a dry or rainy winter season, or dry or rainy summer season. Table 1 gives the names of the regions, their relative importance, abbreviations used in this paper and the type of potato crop produced. Although total potato production and consumption are rising steadily (Potatoes South Africa, 2015), there is concern in the South African potato producing community about its competitiveness in a globalizing market, especially with frozen potato products becoming a globally traded commodity. Competiveness can be enhanced by improved use of resources – land, water, energy, labour, machinery, fertilizers and pesticides – and by reducing risks. The potato crop is subjected to numerous abiotic and biotic risks, which affect sustainability of production.

Abiotic constraints related to potato production in South Africa are primarily temperature and precipitation related events (Steyn *et al*., 1998; Franke *et al.*, 2013; Haverkort *et al*., 2013). Potato crops in the various regions may suffer from low temperatures such as late frosts which occur after winter, early in the planting season thus damaging crops after emergence; or early frosts at the beginning of winter which kill crops prematurely (Haverkort *et al*., 2013).

Table 1[1]. Agro-ecological conditions during the growing season of potato production regions in South Africa (Potatoes South Africa, 2013 harvest figures)

#	Region	Growing conditions	Total solar radiation ($MJ\ m^{-2}$)	Temperature Mean (˚C)		Main planting month**	Total rainfall (mm)	Predominant soils
				Maximum	Minimum			
1	Eastern Free State	Wet summer	2872	24.5	11.5	Sep	319	Loam
2	Limpopo	Dry winter	2368	25.8	9.3	Jun	37	Loam
3	Western Free State	Wet summer	2588	28.4	12.1	Jan	230	Sand – sandy loam
4	Sandveld	Wet winter / dry summer	2219	23.3	6.3	Jun	127	Sand
5	KwaZulu-Natal	Wet summer	1739	24.3	12.9	Aug	251	Loam- clay loam
6	Highveld	Wet summer	2442	25.2	8.2	Aug	246	Sandy loam
7	North West	Wet summer	2621	28.7	9.4	Aug	127	Sand
8	North Eastern Cape	Wet summer	2125	21.6	9.7	Sep	326	Sandy loam
9	Northern Cape	Wet summer	2479	28.9	13.2	Jan	184	Sandy loam - loam
10	E Cape	Wet summer	1731	22.8	9.5	Jul	181	Loam
11	Loskop Valley	Wet summer	1946	24.2	5.6	May	18	Sandy loam
12	Ceres	Wet winter	2140	25.1	11.1	Oct	107	Sand
13	SW Free State	Wet summer	2219	27.4	9.0	Aug	142	Sandy loam
14	Gauteng	Wet summer	1996	23.3	7.9	Jul	111	Loam - clay loam
15	Southern Cape	Wet summer / winter	1413	19.6	8.9	Jul	242	Sandy loam
16	SW Cape	Wet winter	1825	21.9	11.3	Aug	406	Sandy

Note: *mean conditions during growing season; ** some regions have more than one planting period, but main period was used in this study.

[1] There is some overlap in introduction and methodology (specifically Tables 1 and 2) with Steyn *et al.* (submitted) as both studies made use of the same survey but addressed different issues.

Heat waves during the growing season and at the time of tuber bulking may lead to temporarily reduced or halted crop growth as well as reduced quality of the tubers (UNECE, 2014). When temperatures drop again, resumed tuber growth leads to secondary growth symptoms and malformation, such as growth cracks and knobbiness (Wale *et al.,* 2008; Denner *et al.*, 2012; Potato Council, 2013). Precipitation related events that pose a risk to potato are excess rain during tuber growth leading to waterlogging, crops rotting in the soil due to asphyxiation, or too much rain at harvest rendering harvest impossible (Wale *et al.,* 2008; Denner *et al.*, 2012; Potato Council, 2013). Too little rain poses risks especially where crops are rain-fed, primarily in the Eastern Free State, although elsewhere drought may lead to restrictions on irrigation from dams or rivers affecting potato production as well. Also after a drought period, secondary growth symptoms and malformation could occur when soil moisture is replenished.

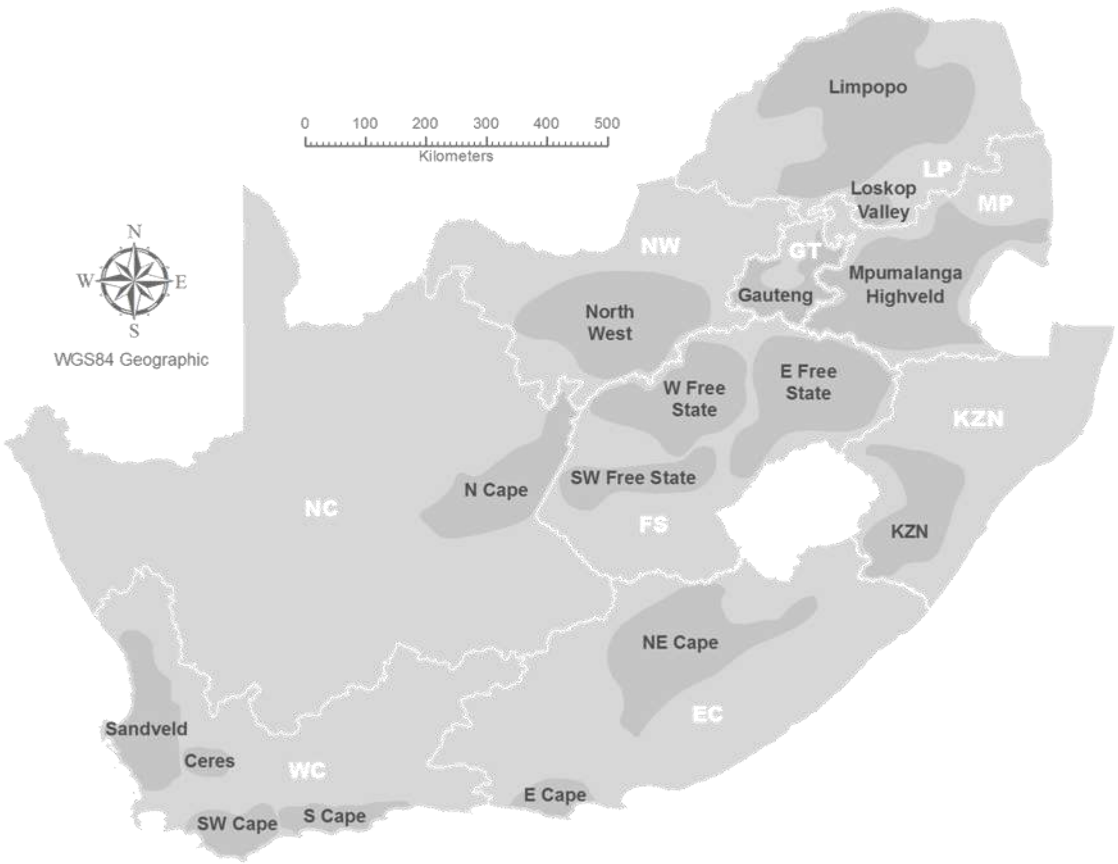

Figure 1. Map indicating the approximate positions of South African potato production regions. EC = Eastern Cape; FS = Free State; GT = Gauteng; KZN = KwaZulu-Natal; LP = Limpopo; MP = Mpumalanga; NC = Northern Cape; WC = Western Cape (L. van Zyl, TerraGIS, South Africa).

The most important air-borne pathogens of potatoes in South Africa are *Alternaria solani* (early blight), *Alternaria alternata* (brown spot) (van der Waals *et al*. 2011) and to a lesser extent *Phytophthora infestans* (late blight). Dominant tuber- and soil-borne fungi and fungus-like are *Rhizoctonia solani* (black scurf), *Helminthosporium solani* (silver scurf), *Spongospora subterranea* f.sp. *subterranea* (powdery scab), *Fusarium* spp. (Fusarium wilt), *Verticillium dahliae* and *V. albo-atrum* (Verticillium wilt) (Denner *et al*., 2012). The incidence and severity of the soft rot / blackleg disease complex in the South African potato industry has increased substantially in recent years, with *Pectobacterium carotovorum* subsp. *brasiliense* being the primary causal agent (van der Merwe *et al*. 2010). Root knot nematodes are common and destructive pests of crops in South Africa (Fourie *et al.,* 2001). *Meloidogyne javanica* and *M. incognita* are the most important species on potatoes in South Africa (Kleynhans *et al.,* 1996). The potato crop is also subjected to diseases caused by viruses (especially Potato Virus Y (PVY) and Potato Leaf Roll Virus (PLRV)), which are primarily vectored to new crops by winged aphids (Hemiptera: Aphididae) (Radcliffe, 1982). Thus, the presence of aphids in a crop is often an indicator of virus infection. Beside aphids, tuber moth (*Phthorimaea operculella*) and leaf miners (*Liriomyza* spp.) are important pests affecting potato crops in South Africa (Denner *et al*., 2012) and were therefore included in this survey.

The aim of the current survey on abiotic risks in South African potato growing regions was to establish the competitiveness of the different regions and develop means to mitigate risks. Also it is assumed that increased risks of abiotic and biotic stresses necessitate growers to increase their inputs (as an insurance) leading to the excessive use of irrigation, fertilisers or seed potatoes in order to mitigate these risks. Knowledge of the incidence and severity of certain risks may assist growers in adapting the mitigation strategies to be more economically sustainable.

The aim of the section of this study regarding biotic influences on potato production was to determine growers' perceptions of the occurrence and severity of pests and diseases in potato growing regions of South Africa, and the frequency of control thereof with biocides. From this information the relative threat from deleterious organisms between regions can be assessed and the justification of the use of biocides established.

2. Materials and Methods

All 16 potato production regions in the country were visited during 2013 and 2014 to conduct surveys on yield losses due to weather events and pests and diseases. The aim of this study

Table 2[2]. Number of table, processing and seed potato growers interviewed per region.

#	Region	Abbreviation	Growers interviewed per production system			# Irrigated / Dryland		Total #	Average area per grower (ha)	Average yield (t/ha)
			Table	Processing	Seed	Irrigated	Dryland			
1	Eastern Free State	EFS	4	2	1	3	4	7	240	21
2	Limpopo	Lim	5	4	0	9	0	9	132	39
3	Western Free State	WFS	6	0	3	9	0	9	90	44
4	Sandveld	SV	7	4	6	17	0	17	68	37
5	KwaZulu-Natal	KZN	7	0	4	7	4	11	64	32
6	Highveld	HV	1	0	4	5	0	5	112	47
7	North West	NW	3	0	2	5	0	5	79	48
8	North Eastern Cape	NEC	4	0	3	5	2	7	155	32
9	Northern Cape	NC	4	1	3	8	0	8	54	34
10	E Cape	EC	3	0	0	3	0	3	90	33
11	Loskop Valley	LV	1	4	0	5	0	5	102	35
12	Ceres	Ceres	3	2	3	8	0	8	61	43
13	SW Free State	SWFS	3	0	0	3	0	3	69	45
14	Gauteng	GT	4	0	0	4	0	4	100	39

[2] There is some overlap in introduction and methodology (specifically Tables 1 and 2) with Steyn *et al.* (2015) as both studies made use of the same survey but addressed different issues.

15	Southern Cape	SC	0	0	3	3	0	3	53
16	SW Cape	SWC	2	0	0	2	0	2	21
	Total		57	17	32	96	10	106	-

was to interview at least three to five growers per region, depending on the size of the region and diversity of production practices (Table 1). Selection of growers was unbiased and random, providing a representative sample of the commercial growers in the country. A total of 106 commercial growers were interviewed, representing almost 20% of all commercial seed, processing and ware potato growers in South Africa (Table 2). The data from the South Western Cape was, however, excluded from the analysis and results, as the number of growers in this region has decreased drastically over the years, to such a point that only two growers were available for interviews.

2.1. Extreme weather events

The frequency of extreme weather events was determined by asking growers to indicate how often over the ten year period (from 2003 to 2012) each of the following weather events had caused more than 25% yield losses. The extreme weather events included in the questionnaire were too much or too little rain (flood or drought, respectively), hail damage, and extreme temperatures (high or low). Growers were also asked to indicate during which stage of the growing season the damages were caused: at planting, during the season, or at harvest. The frequencies of different abiotic risks in a region were accumulated to achieve a combined score for abiotic risks in a region.

2.2. Diseases and pests

Growers were asked whether certain important potato pathogens and pests were observed on their farm during the period 2008 - 2012 and if so, if the associated yield losses when control practices were applied, were more or less than 3%. The pests and diseases concerned were three insects (tuber moth, leaf miners and aphids), root knot nematodes, two viruses (PLRV and PVY), eight fungal diseases (silver scurf and black dot, black dot, powdery scab, fungal wilts (*Fusarium* and *Verticillium*), brown spot, early and late blight) and two bacterial diseases (common scab, and the blackleg / soft rot disease complex).

For each region and pathogen or pest, occurrence and a severity index were calculated, based on the answers given by growers. Occurrence was calculated as the number of growers who reported the presence of the pathogen or pest on their farm, divided by the total number of respondents in that region (presented as a percentage). The severity index was calculated as the number of growers who regarded the yield losses due to a specific pathogen or pest as more than 3%, divided by the total number of respondents in that region and then multiplied by the occurrence value previously calculated. Growers were also asked to provide information about the seed- and soil treatments applied, as well as number of insecticide and fungicide spray applications during the growing season. Long-term weather data for each region was obtained from the Agricultural Research Council (ARC-SCW).

Relationships between pest or disease occurrence and severity and between weather events and pest or disease occurrence or severity were assessed using Spearman's Rank Correlation Test. In cases where the sample size was too small for analysis using this test, Kendall's test was used instead. Simple linear regression analysis was also used to assess relationships between variables in case a causal relationship was expected. The results from this survey were communicated to growers during interactive grower days in each region, to provide guidance to them regarding sustainable pest and disease management and mitigation measures for extreme weather events.

3. Results and Discussion

3.1. Extreme weather events

As indicated in Figure 2, in Gauteng potato production is perceived to be most risky in terms of extreme weather events. Here the cumulative risk is almost 10, meaning that on average every year in 2003 – 2012 an extreme weather event resulted in yield losses of 25% or more. The main causes of yield loss in this region are too much rain, hail and frost. This suggests that yields in Gauteng could be up to 25% higher than the current average 48.1 t/ha if these abiotic risks could be avoided or the effects thereof mitigated. The second region most prone to extreme weather events is the Eastern Free State, followed closely by Limpopo. The greatest risks in the Eastern Free State are too much rain during the growing season, dry spells and occasional hail. Limpopo growers' greatest challenges are extreme temperatures, too much rain in the summer planting season and a small chance of hail. The region perceived to be the least risky for growing potatoes is the Sandveld, with only high temperatures in summer plantings posing a threat. Without the abiotic risks in the Sandveld, yields may be 4.5% higher than what they are currently (49.2 t/ha).

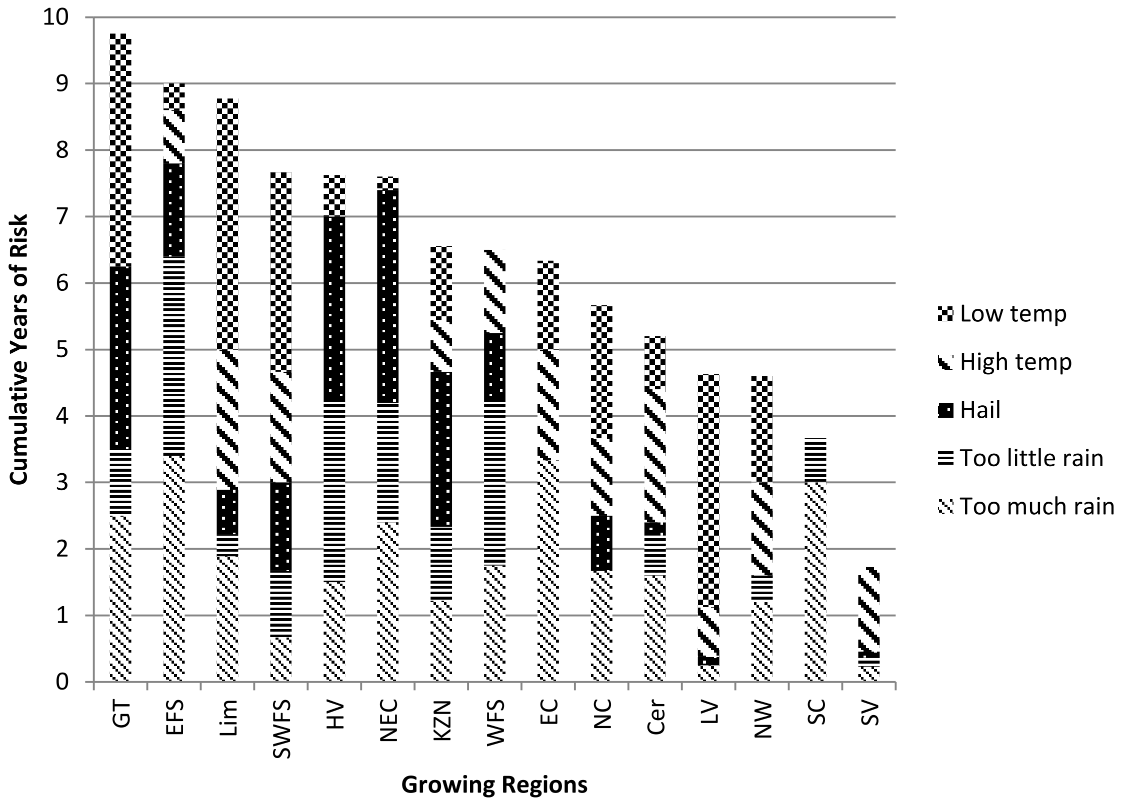

Figure 2. Cumulative frequency of weather events causing more than 25% crop damage between 2003 and 2012 in potato growing regions in South Africa.

Hail is responsible for extensive damage to crops in the South Western Free State, the Highveld, the North Eastern Cape, KwaZulu-Natal and the Western Free State, while too much rain often occurs in Gauteng, the North Eastern Cape, the Eastern Free State, the Eastern Cape and the Southern Cape. In areas prone to severe hail storms, growers often insure crops against yield losses due to hail damage. It is important that growers are able to quantify the frequency and severity of these events, to determine the economic feasibility of such insurance.

Drought is a recognisable risk in the Eastern Free State, which is predominantly a rain-fed growing region. However in regions which irrigate from dams, such as the Highveld, North Eastern Cape and eastern parts of the Western Free State, drought in the preceding season can result in low dam water levels and consequently water restrictions on irrigation.

Despite South Africa being a relatively dry country, too much rain appeared to be one of the most common abiotic risk factors for potato production in South Africa. This is partly because South Africa’s mean annual precipitation is highly variable (Tyson, 1986; Mason & Jury, 1997), but also because of the untimely occurrence of heavy rainfall events. In areas where crops are planted in poorly drained soils, anaerobic conditions in the soil after heavy rainfalls in the beginning of the season can lead to rotting of the seed potatoes. During tuber bulking erratic rainfall events could result in physiological growth cracking, tuber malformation and rotting, while heavy rainfalls at the end of the season will delay harvest and increase the incidence and severity of various tuber diseases and defects, such as soft rot, black dot, white mould, powdery scab and hollow heart (Adams & Stevenson, 1990).

In Gauteng late frosts affect many of the growers who plant early in spring to market their potatoes in mid-summer. These growers should weigh up the advantages of marketing in mid-summer against the losses incurred due to late frosts. In Limpopo, the Eastern Cape, the South Western Free State and Loskop Valley mid-season frosts can kill or severely set the potato plants back, thus significantly reducing yields. The frost risk in these regions is also weighed up against the opportunity of fetching higher market prices in September to December. Usually prices are higher at this time as other regions such as the Western Free State, Eastern Free State and Highveld have finished marketing, so volumes on markets are lower, resulting in higher prices. In the Northern Cape most of the losses are due to early frosts which occur at the end of the growing season. In this case, earlier plantings might reduce the risk of losses due to frosts at the end of the growing season (van der Waals *et al*., 2013).

3.2. Diseases and pests

Pathogen and pest occurrence and severity indices varied considerably between organisms (Fig. 3). Much of the variation can be attributed to differences in planting season and environmental factors (Table 1). Based on the severity index, the silver scurf / black dot disease complex and tuber moth are perceived by growers to cause most losses of all the diseases and pests in question. These data confirm reports in recent years which have shown that black dot and silver scurf are diseases which are increasing in importance in global potato production (Erampalli *et al*., 2001; Avis *et al*., 2010). These were followed closely in severity by early blight, the blackleg / soft rot disease complex, and leaf miners. The most predominant pests and diseases in the country were tuber moth, leaf miner, aphids and early blight, with 98%, 97%, 88% and 88% of growers reporting the occurrence of these pests and diseases, respectively, on their farms between 2008 and 2012 (Fig 3). This data may be partly biased as growers recognise insect pests more easily than some of the fungal and bacterial diseases such as powdery scab, which had the lowest occurrence and second lowest severity index.

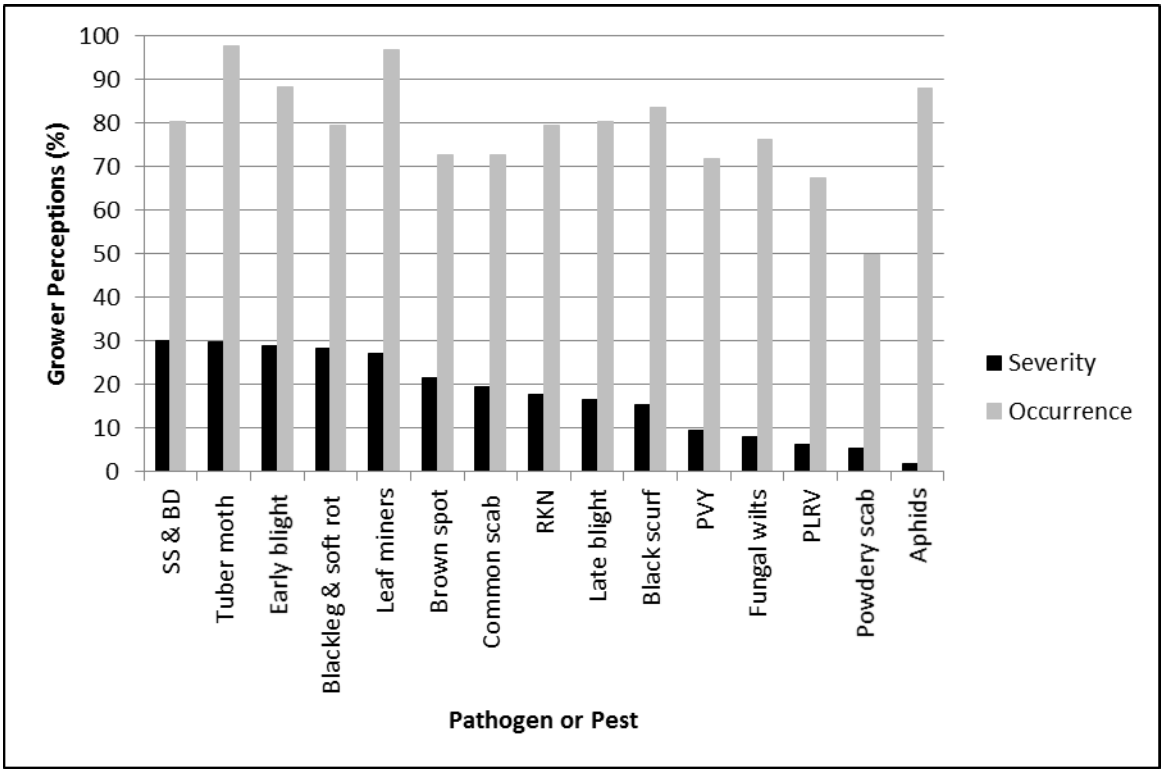

Figure 3. South African potato growers' perceptions of the occurrence and severity of various diseases and pests on their farms, for the period 2008 - 2012.

Despite a positive trend, there was no significant correlation using Spearman's ranking between total pest and disease occurrence and total severity index for the country, or for most of the organisms when analysed on their own, for example late blight and tuber moth ($t = 0.379$ and $t = 0.138$, respectively). However, in a few cases, such as the silver scurf / black dot and blackleg / soft rot disease complexes respectively, a significant positive correlation was observed between occurrence and severity indices ($t = 0.009$ and $t = 0.017$, respectively). The variations in correlation between occurrence and severity can be explained by the differences in efficacy and availability of control methods, as well as time of symptom expression. In the case of late blight and tuber moth, pesticides are usually applied preventatively if the grower is aware that the pathogen or pest is present in the area. Thus, occurrence will not be linked to severity. Silver scurf and black dot are normally only observed on tubers at harvest when qualitative yield losses linked to reduction in marketability or seed certification have already been incurred (Erampalli *et al*., 2001; Avis *et al*., 2010). In the blackleg / soft rot disease situation, no chemicals are available to control this disease (Charkowski, 2015), thus occurrence is often linked to severe quantitative yield losses.

When considering each biotic threat individually, it was noted that late blight was reported to occur in all regions; although not all respondents in all the regions recorded having observed the disease on their farms in the past five years (Fig. 4a). The lowest occurrence was recorded in the North West growing region and the national average was 80%. The only regions where the disease was perceived to cause yield losses above 3% were the Eastern Cape, KwaZulu-Natal, the Eastern Free State, Limpopo, Gauteng and the Sandveld (in order of decreasing importance) (Fig. 4a). In all these regions, there was a likelihood of cold, wet or humid conditions during the growing season (Table 1), thus providing a favourable environment for the development of late blight (Harrison, 1992). The average severity was 17%, indicating that although the disease can cause yield losses in some regions, *P. infestans* is not considered a destructive pathogen in South Africa. This is due to the predominantly hot and dry climatic conditions in South Africa, as well as the fact that the A2 mating type is not present in the country (Pule *et al.,* 2013).

The average occurrence of early blight was relatively high at 88% and respondents in nine out of the 15 regions indicated that yield losses incurred due to early blight are greater than 3% (Fig. 4b). As most of the potatoes were grown in summer under irrigation, environmental conditions are highly favourable for the development of early blight in South Africa (van der Waals *et al*., 2001). Losses due to early blight were perceived to be highest in the Eastern Free State and North Eastern Cape.

Brown spot, caused by *Alternaria alternata*, was reported to occur in all growing regions, with the exception of the Eastern Cape (Fig. 4c). The national occurrence of this emerging disease was 73%. Similarly, and for the same reasons as the early blight severity results, brown spot reportedly caused yield losses of more than 3% in nine of the 15 growing regions (Fig. 4c). The brown spot severity index was highest in the South Western Free State growing region.

Since it is often difficult for growers to distinguish between *Fusarium* and *Verticillium* wilts in the field (Fradin & Thomma, 2006), these two diseases were grouped together as “fungal wilts” in this study. The average incidence was 76%, with the diseases being reported in all regions, but the losses incurred due to these wilts were much lower than those caused by late blight, early blight or brown spot (Figs. 3 and 4d). Respondents from only six regions reported yield losses of more than 3%, with the highest severity index in the Eastern Cape (Fig. 4d).

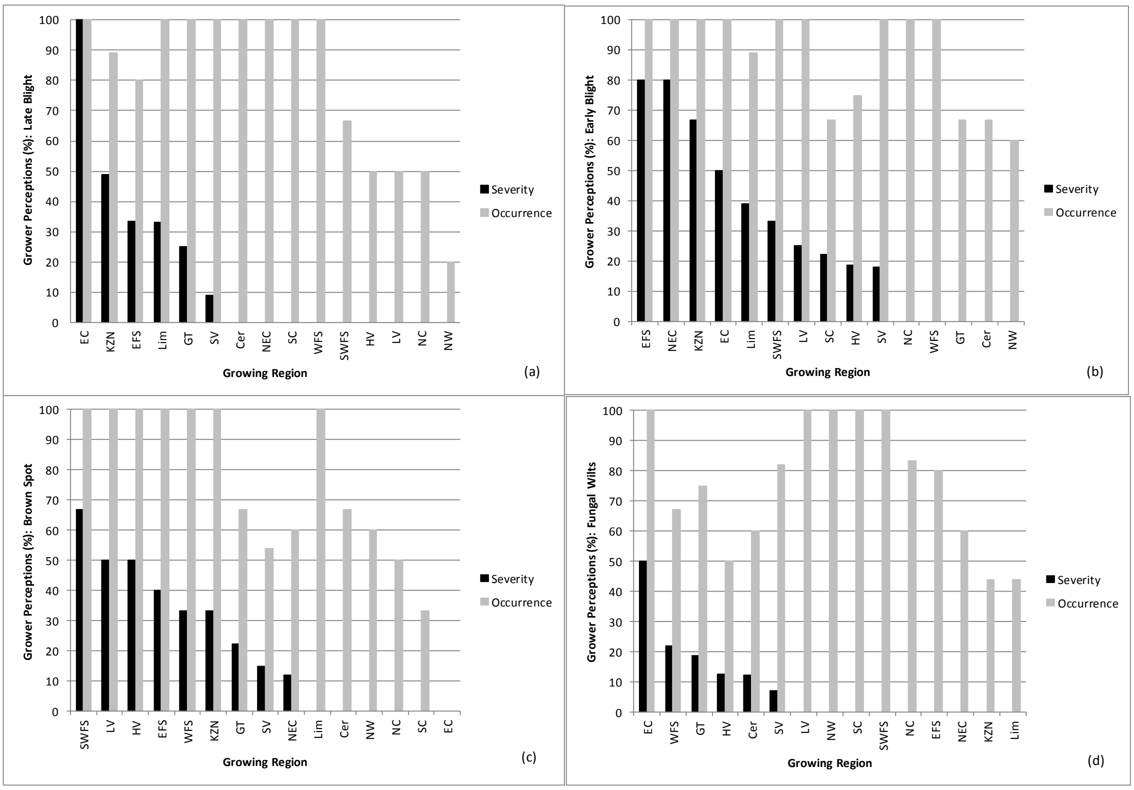

Figure 4. Severity and occurrence indices for (a) late blight, (b) early blight, (c) brown spot and (d) fungal wilts in the potato growing regions of South Africa, for the period 2008 - 2012.

There was no significant relationship between the severity or occurrence of foliar diseases and average rainfall in the growing season . When rainfall events create favourable environmental conditions for disease development and spread, disease pressure increases and control is ineffective or difficult (Potato Council, 2013; UNECE, 2014).

There was a significant positive correlation between hail and brown spot severity (t = 0.038), using Spearman's ranking. *Alternaria alternata* is an opportunistic pathogen (Thomma, 2003) and thus the severity of the disease can be expected to be higher after hail storms.

The blackleg and soft rot disease complex was reported to occur in all growing regions although only five regions had occurrences of 100% (Fig. 5a). This is not surprising as the causal agent is primarily seed-borne (Lim, 1975; Pérombelon & Hyman, 1988; Ali *et al*., 2012), and seed movement and trade within the country is not restricted. The average occurrence was 79%; and respondents in 10 of the 15 regions stated that this disease complex causes yield losses of more than 3%, with an extremely high severity index in the Eastern Cape (Fig. 5a).

The average occurrence of common scab was 73%, with the disease being reported in all regions except the Loskop Valley. This could be due to the fact that growers in the Loskop Valley plant in cooler periods of the year, thus escaping infection by *Streptomyces* spp.. The profile for common scab severity index was similar to that for blackleg and soft rot, with yield losses of more than 3% in 11 of the 15 regions, and an extremely high index value in the Eastern Cape (Fig. 5b). Besides the Loskop Valley, only the KwaZulu-Natal, Gauteng and Western Free State growers stated that common scab did not cause serious yield losses. In KwaZulu-Natal, the turf soils and cool, moist conditions were not conducive to the development of common scab (Loria *et al.,* 1997). In Gauteng and the Western Free State, the predominant cultivar planted (Mondial) was relatively tolerant to common scab (Potatoes South Africa, 2015).

Powdery scab occurrence and severity index values were considerably lower than those for the other diseases, with an average occurrence of 50% (Fig 5c). Respondents in the Highveld and the Loskop Valley growing regions did not report the presence of the disease on their farms during the period in question (Fig. 5c.) Yield losses above 3% were only noted in six regions, with the disease index once again being highest in the Eastern Cape (Fig. 5c). The national severity average was only 5%, despite the fact that powdery scab can be considered one of the most economically important diseases in the South African potato industry (J.E. van der Waals, personal observation).

In contrast to powdery scab, black scurf was reported to occur in all growing areas and the average occurrence was 83% (Fig. 5d). Eight of the 15 regions surveyed reported yield losses of more than 3% due to black scurf with the highest severity index once again being reported in the Eastern Cape (Fig. 5d). All of these eight regions plant during cold, wet conditions and on predominantly heavier soils, with the exception of the Northern Cape. These are conditions favourable for the development of black scurf on potato (Carling & Leiner, 1990).

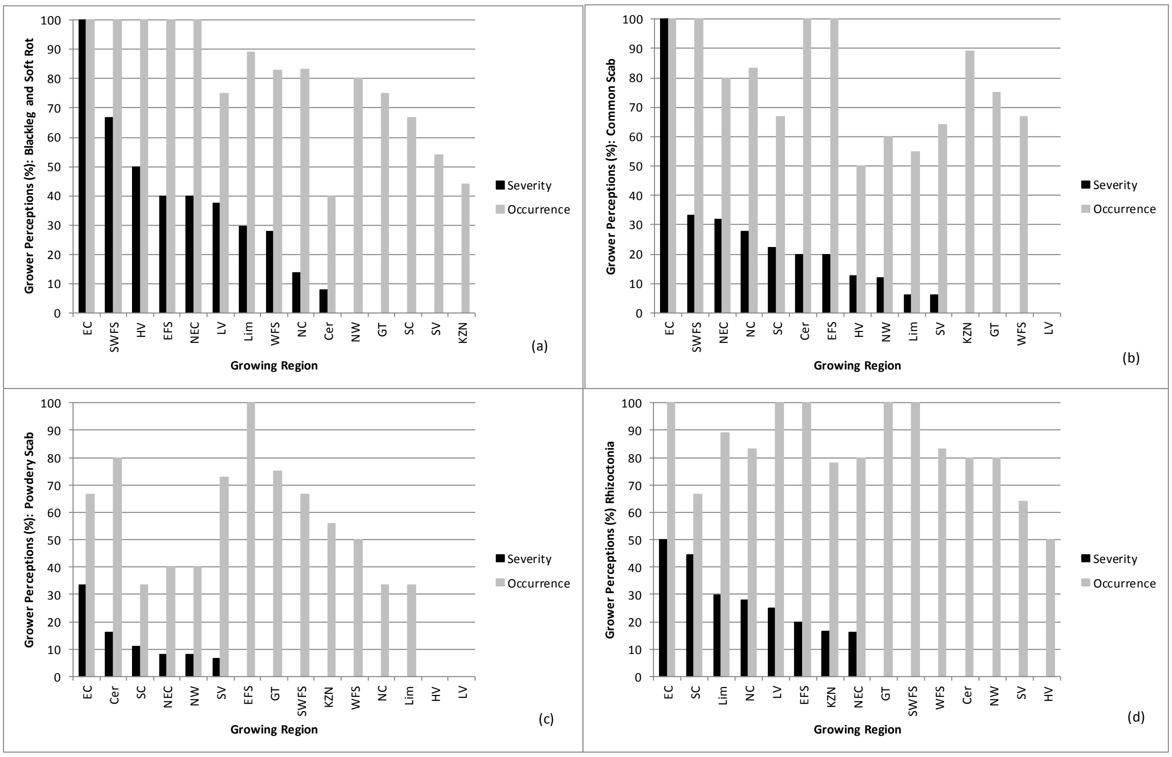

Figure 5. Severity and occurrence indices for (a) blackleg and soft rot, (b) common scab, (c) powdery scab and (d) black scurf in the potato growing regions of South Africa, for the period 2008 - 2012.

The tuber diseases silver scurf and black dot often co-occur and are easily misdiagnosed (Errampalli *et al.,* 2001; Lees & Hilton, 2003) and were thus grouped together in this questionnaire. This disease complex was reported to occur in all growing regions (Fig. 6a). Severity indices indicated the importance thereof in the South African potato industry. All but three regions reported the disease complex to cause yield losses above 3%, with a national severity index of 30%, the highest of all the pests and diseases surveyed (Fig. 6a). There were no commonalities among the eight regions in which this disease complex caused yield losses >3%. Potatoes are not commonly kept in cold storage in South Africa, as they are in many countries in the Northern Hemisphere. However in some of the eight regions potatoes are stored in the soil during cool conditions before harvesting, while in others heavy, moist soils at harvest prevent early lifting of potatoes. Both practices lead to an increase in disease development (Errampalli *et al*., 2001; Lees & Hilton, 2003). In seed producing regions such as the Western Free State and Ceres, which both have sandy soils, yield losses due to the disease were probably perceived to be high, as disease severity ranging from >0.5% in Elite G1-G3 seed to >30% in Standard G4-G8 seed will lead to downgrading or rejection of the seed (Potato Certification Service, 2015). These data corroborate with that from other studies, which have shown that both diseases are increasingly important in potato production globally (Errampalli *et al*., 2001; Lees & Hilton, 2003).

In the case of Potato Virus Y (PVY), respondents in all regions acknowledged the presence of the virus on their farms (Fig. 6b). The average occurrence of PVY was 72%, but yield losses greater than 3% due to this virus were only reported in six regions (Fig. 6b). A similar picture was observed for Potato Leaf Roll Virus (PLRV). Although it was also reported to occur in all growing regions, the average occurrence was 67% and only five regions recorded losses greater than 3% due to the occurrence of this virus (Fig. 6c). The severity of these viruses in seed crops was kept low due to the Potato Seed Certification Scheme (Potato Certification Service, 2015). There were no distinct correlations between the regions where these viruses were reported to cause severe losses and climate, rotational crops or type of potato crop produced.

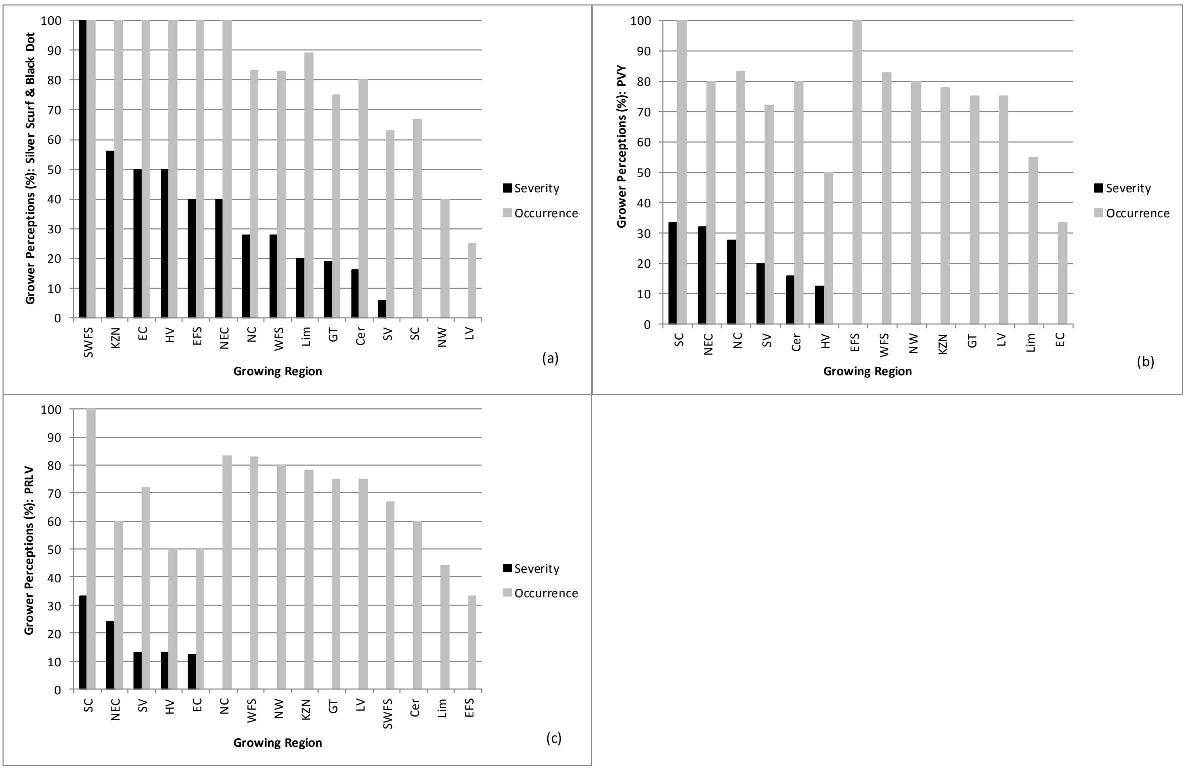

Figure 6. Severity and occurrence indices for (a) silver scurf & black dot, (b) Potato Virus Y (PVY) and (c) Potato Leaf Roll Virus (PLRV) in the potato growing regions of South Africa, for the period 2008 - 2012.

The occurrence of aphids, leaf miners and tuber moth (90%, 97% and 98%, respectively) (Fig 7a, b, c) was much higher than those of the diseases surveyed. Losses incurred due to aphids were only considered higher than 3% in three of the 15 regions (Fig. 7a), while respondents from 11 and 12 regions reported yield losses greater than 3% due to leaf miner and tuber moth, with national severity indices of 27% and 30%, respectively (Fig. 7b, c). Many growers commented that the numbers of leaf miners in the potato crop increase substantially after harvest of neighbouring vegetable crops. Communication of this observation to other growers can help assist in correct timing of insecticide applications, thus allowing for better management of this pest. In order to reduce severe outbreaks of leaf miners, proactive management decisions must be made and all growers in a region must adopt similar IPM strategies so that one or a few growers do not adversely affect neighbouring growers (Reitz *et al*., 2013).

As with PVY and PLRV, Root Knot Nematode (RKN) was reported to occur in all regions (Fig. 7d). The average occurrence was 79% and respondents from ten of the 15 regions considered the yield losses caused by this pest to be greater than 3% (Fig. 7d).

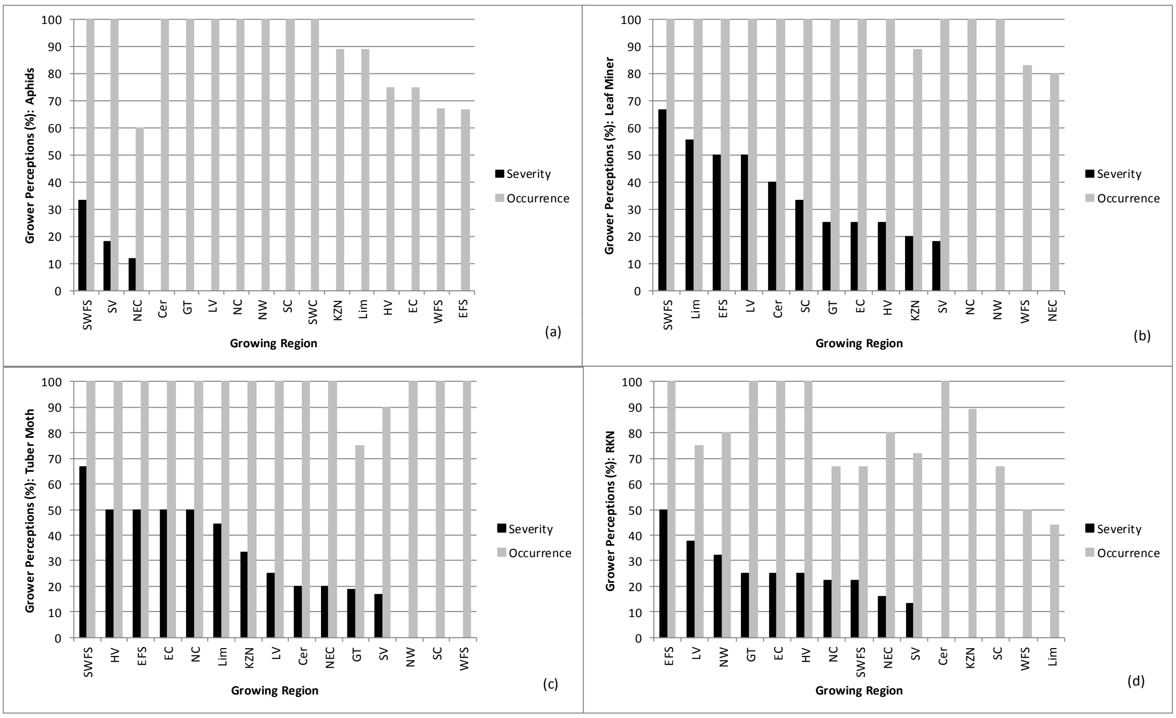

Figure 7. Severity and occurrence indices for (a) aphids, (b) leaf miners, (c) tuber moth and (d) root knot nematode in the potato growing regions of South Africa.

Cumulative pathogen and pest severity index was highest in the Eastern Cape and lowest in the North West growing region. Distribution of pathogens and pests throughout the regions was relatively even (Fig. 8). The Eastern Cape has an average crop rotation cycle of less than three years and potatoes are grown year-round, which will result in a constant increase in inoculum and thus high disease pressure. The only pathogens and pests which were not reported to cause yield losses greater than 3% in this region were brown spot, PVY, PLRV and aphids. Brown spot is likely to be a serious problem in the Eastern Cape production region, due to the previously mentioned production practices and climate in the region, but has most likely been misdiagnosed by growers. There were no seed growers in the Eastern Cape, and thus viruses and the aphid vector were not perceived to cause serious losses. For certification purposes two compulsory field inspections are conducted on seed growers' farms during the season (South African Seed Potato Certification Scheme, 2013), however this is not required for table or processing potato growers. Thus, seed growers were acutely aware of the problems aphids cause in their fields, in terms of vectoring viruses which may result in rejection or downgrading of seed crops.

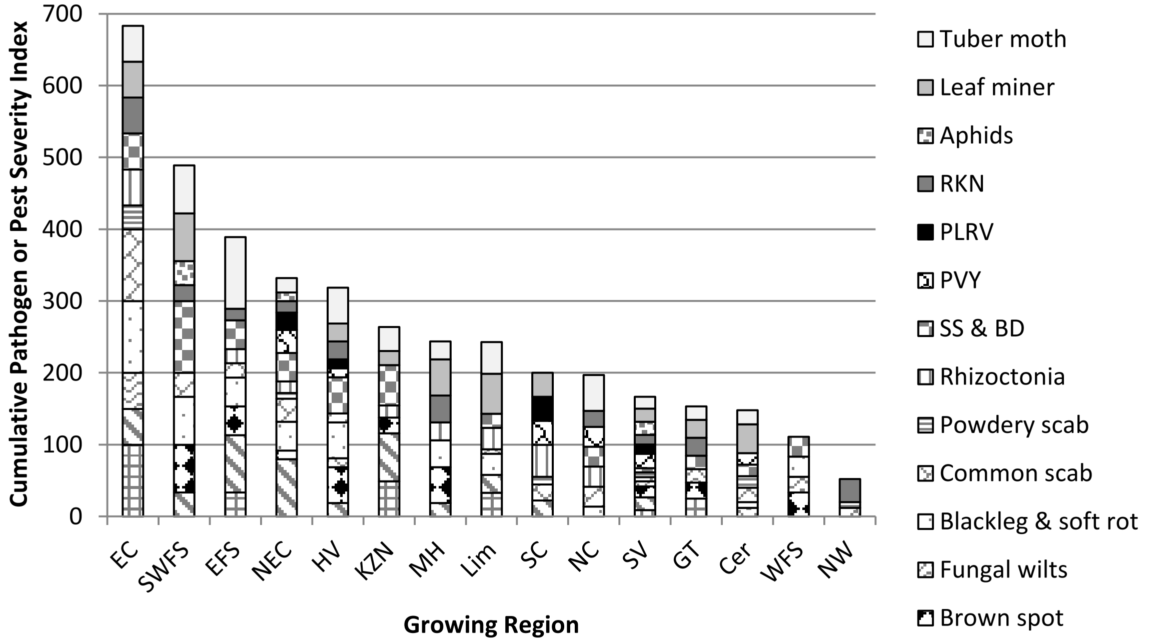

Figure 8. Cumulative pathogen and pest severity indices for the different potato growing regions in South Africa, for the period 2008 - 2012. RKN = Root Knot Nematode; PLRV = Potato Leaf Roll Virus; PVY = Potato Virus Y; SS = Silver Scurf; BD = Black Dot.

The South Western Free State ranked second highest in terms of cumulative pathogen and pest severity index. This region has a rotation cycle of 4-5 years and only a summer planting. Disease pressure in this region was probably high due to hot summers, overhead irrigation and sandy soils, which resulted in plants growing under stressed conditions and thus being more susceptible to attack by pathogens and pests. Diseases and pests that were not reported to cause serious yield losses in this region were late blight, fungal wilts, black scurf, PVY and PLRV. The first three can be explained by the hot conditions under which potatoes were produced, which were unfavourable for the development of these

Table 3. Average potato producer prices in USD / tonne for 2011 – 2013 for selected countries (Source: FAOSTAT, 2015).

Country	Producer Price Ave 2011-2013 (USD/tonne)
Australia	510
Israel	718
NL	207
SA	300
Germany	242
Argentina	206
Belgium	188
UK	276
USA	205

Table 4. Number of biocide applications per season for each farm surveyed in the South Western Free State growing region

Grower number	Seed Treatments	Soil Treatments	Insecticides	Fungicides
1	1	1	11	11
2	2	2	7	7
3	0	1	13	13
4	1	1	11	11
5	2	2	7	7
6	0	1	13	13
7	0	2	14	14
8	0	1	11	11

diseases. Potato production in this region was all ware and thus losses incurred due to virus infection were not regarded as important.

Growers in the North West regarded only three biotic risks as causing yield losses more than 3%, namely common scab, powdery scab and root knot nematode. Planting times in this region ranged from August to February, but the major growing season was summer. Potatoes were irrigated and soils are sandy with pH values ranging from 4.5-8.0. None of the foliar diseases, viruses or insects were regarding as economically important. This was probably because of the long crop rotation cycles, which were between four and 10 years, depending on the availability of land. In addition potato production in the North West is relatively isolated; farms were far apart and not many other crops were produced in this region.

Large differences were observed in farm-level management of pests and pathogens, both between regions (Figure 9), and among growers within regions; refer to the South Western Free State as an example (Table 4). There was no significant relationship between occurrence of diseases and pests, and the number of biocides applied by growers, but a weak negative relationship was observed between severity of damage caused by diseases and pests and number of biocides applied on farms (data not shown). There were also no significant relationships between applications of specific biocides and the occurrence or severity of the target organism(s).

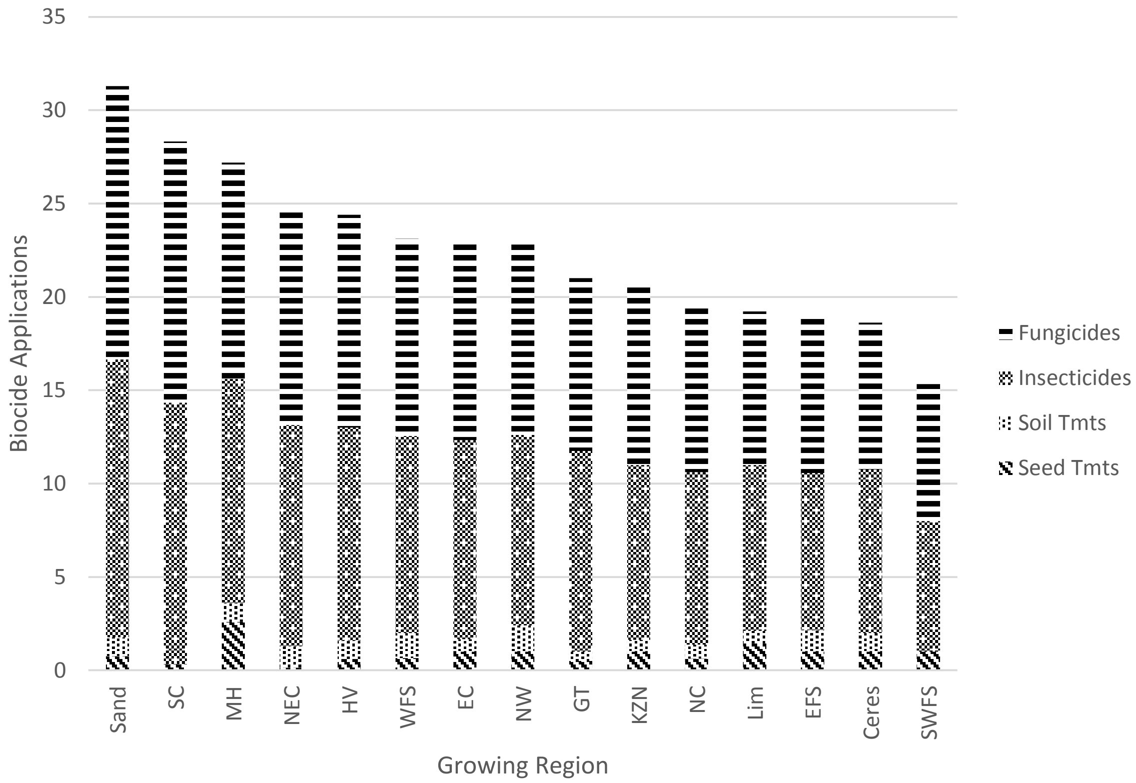

Figure 9. Total number of biocide applications per season for each potato growing region in South Africa, for the period 2008 - 2012.

A negative, but not significant, relationship was found between extreme weather events and yield, as well as between pest and disease severity and yield. Biotic risks, however were shown to pose a greater risk to potato yield reduction in South Africa than abiotic risks.

4. General Discussion

Knowledge of the frequency of weather events in each growing region enables us to (i) benchmark regions in terms of risk, (ii) identify most appropriate measures of mitigation and communicate these to growers, and (iii) possibly in future, investigate options for expansion of production to new growing regions in case current regions cannot cope with the demand, e.g. due to a changing climate, reduced water availability or an increasing demand. The feedback sessions highlighted the need for regular, focused researcher-grower interactions. Most growers were keen to discuss the yield losses caused by abiotic factors, and actions taken to mitigate them. In the majority of cases there was also a positive discourse and exchange of ideas among growers and researchers regarding pest and pathogen problems, and control strategies applied. The same response from growers was observed in the survey conducted by Dillard *et al.* (1993) in South Australia.

Although growers' answers from this survey were perceptions and not necessarily a true reflection of the pest or pathogen status in a region, the results obtained generally correlated well with the expected pathogen or pest occurrence and severity in each region based on prevailing climatic conditions, with the exception of powdery scab and brown spot. Growers' responses regarding the occurrence and severity of brown spot substantiated the results of Breukers *et al.* (2012) from their study on decisions made by growers to manage invasive pathogens at farm level. They concluded that knowledge of a pathogen, being made aware of its presence and previous experience with it, were interrelated. The grower can only perceive risk presented by a pathogen or pest when they are aware of its existence. Brown spot can be considered a new disease in South Africa (van der Waals *et al.*, 2011) and has increased in importance and severity in almost all growing regions in the past decade (Dube *et al.,* 2014). Unpublished data from the Potato Pathology Programme Diagnostic Clinic at the University of Pretoria and personal observations in the field by the first author indicate that brown spot has caused more yield losses than early blight in most growing regions over the past five years. This was, however, not reflected in the responses from this survey, suggesting that growers may be unable to recognise the symptoms of brown spot.

Similar explanations can be provided for the discrepancy in perceptions and reality of the importance of powdery scab. Firstly, powdery scab symptoms can easily be confused with those of common scab, especially in the early stages of the disease (Bouchek-Mechiche *et al.,* 2011; Qu *et al.,* 2011). Growers not trained to distinguish between the two diseases might easily make an incorrect diagnosis. Secondly, because the survival structures of the pathogen *Spongospora subterranea* f.sp. *subterranea* persist for decades in the soil (Merz & Falloon, 2008) and because tuber lesions render potatoes unmarketable or cause rejection of seed lots, growers might be hesitant to admit the presence of the pathogen on their farm or the severity of disease at harvest. The first author observed yield losses due to powdery scab far in excess of 3% in a number of growing regions over the past five years; however growers in these regions did not regard the disease as causing major yield losses.

Grower perceptions of occurrence and severity of pathogens or pests are not only related to their ability to correctly identify the disease or pest, knowledge of the epidemiology of the disease (Breukers *et al.,* 2012), but also to the frequency of field visits and harvest inspections done, and willingness to share information. The case of PVY and PLRV is an example of how knowledge of a certain pest or pathogen affects the perception thereof.

Breukers *et al.* (2012) quantified "knowledge" in two ways, namely, recognition of symptoms and knowledge of sources of introduction on the farm. The symptoms of PVY are difficult to recognise and physiological disorders can be easily mistaken for PVY infection. This could have lead certain growers to perceive losses due to PVY to be higher than they actually were. We would have expected the values for PVY / PLRV and aphids to be very similar, but this was not the case, thus substantiating the argument.

The lack of significant relationships between the number of biocides applied and perceived occurrence of the target organism(s) indicated that the majority of growers did not use any form of detection or forecasting models in their disease and pest management programmes. It is clear from our results that growers use biocide applications as a relatively cheap insurance against pests and pathogens, as also observed outside South Africa. Dillard *et al.* (1993) conducted a similar survey among potato growers in South Australia and their results showed the need for demonstration programs on the use of disease forecasts, such as those developed for early blight. A review by Gent *et al.* (2011) highlighted that, despite the extent and diversity of available disease prediction systems, only a minority of growers have adopted such systems and often only for a limited period of time. Among the reasons provided for this are that (i) use of such models provides the grower with experience in successful crop management, which can be achieved without the use of the model and thus use thereof is discontinued after a while, (ii) information provided by grower education and growers' advisors nullifies the need for a prediction model, (iii) growers are not willing to risk a severe yield loss as a trade-off for what may only have a limited economic advantage (Gent *et al.,* 2011). Scientists and research or extension officers should focus on alerting growers to the availability and usefulness of decision support systems in South Africa, e.g. PLANT-Plus for early blight (van der Waals *et al.,* 2003). Bentley & Thiele (1999), Doré *et al.* (2011) and Schaap *et al.* (2013) also emphasised the importance of knowledge exchange between growers and crop management experts, such as extension officers and applied scientists, in prioritisation and design of farm level adaptation strategies for multiple risk scenarios.

This survey indicates that the biotic and abiotic risks of potato production in South Africa were varied and often resulted in significant yield losses. This was due to the diverse and often unfavourable conditions in which potatoes were produced. Lack or excess of rain was the main abiotic cause of yield reduction of potato in South Africa. Studies by Franke *et al.* (2011) and Steyn *et al.* (2015) showed that the yield gap between potential (calculated using models) and actual yield varies between potato growing regions in South Africa. According to FAO data (FAOSTAT, 2015), the average producer prices of potatoes from 2011-2013 in

South Africa were higher than that of prices in the Netherlands, Germany, Argentina, Belgium, the United Kingdom and the United States of America (Table 3). This indicates it is less cost effective to produce potatoes in South Africa than in these countries, which makes South African potato growers less competitive on a global scale. Nonetheless, locally the demand for potatoes is high, making the industry economically viable. When the South African potato prices were compared to prices in countries with similar biotic and abiotic challenges, such as Australia and Israel, the picture changes dramatically, where the costs of producing potatoes were 1.5 to 2.5 times higher.

This is the first survey of the perceptions of South African potato growers of the risks affecting production. The results of this study, although affected by responder bias, can serve as a baseline on which to benchmark pest and pathogen spread, increase and trends, when similar studies are conducted in future. Future surveys could include sampling of fields in season and at harvest to confirm answers of growers. It is however, important to remember that since this study presents perceptions and not accurate scientific assessments, scientifically conducted surveys may prove these perceptions to be incorrect. Nonetheless, the current results can be used as guidelines for planning research and development programmes for sustainable pest management of potatoes in South Africa and in other potato producing countries with similar conditions. Many previous studies have highlighted the additional stresses that climate change will place on potato production, not only in terms of changing weather patterns but also shifts in pest and pathogen populations (see for example Coakley *et al.,* 1999; Hijmans 2003; Kapsa 2008; Savary *et al.,* 2011; van der Waals *et al.,* 2013). According to the study by van der Waals *et al.* (2013), root-knot nematodes, *M. persicae*, early blight, brown spot and the soft rot / blackleg disease complex are likely to increase in intensity in most potato growing regions in South Africa over the next 25 years. This could be the case for other potato growing regions with similar climatic conditions, such as Israel and certain parts of Australia, North and South America. It is important that scientists and extension officers are in constant communication with growers and those involved in potato production, to inform them about these imminent pest and pathogen shifts and the latest agricultural technology, high yielding or resistant varieties and biotechnological advances, which can be used to improve the resource use efficiency and thereby the competitiveness of potato producers in South Africa and elsewhere.

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