Influence of growth regulators on skin colour and scab diseases of red-skinned potatoes

D. Waterer

Department of Plant Sciences, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A8.
Received 5 March 2010, accepted 1 June 2010.

Waterer, D. 2010. **Influence of growth regulators on skin colour and scab diseases of red-skinned potatoes**. Can. J. Plant Sci. **90**: 745–753. A uniform dark red skin colour is desirable in table potatoes; however, the colour of the popular red-skinned cultivar Norland is variable and tends to fade during storage. This study evaluated the potential to enhance skin colour of red potatoes by foliar application of the auxin-type herbicide 2,4-D or long-lasting analogs of the naturally occuring hormone abscisic acid (ABA). In field trials conducted from 2007 to 2009, the plant growth regulators (PGR) were applied to the foliage of Norland and AC Peregrine Red (a new dark red variety) potato plants when the crop was at the tuber set stage. Although the 2,4-D treatments altered the appearance of the foliage they had no consistent impact on yields or tuber shape, but did reduce the average tuber size. Objective and subjective assessments indicated that the 2,4-D treatments altered the skin colour of the tubers both immediately after harvest and after extended cold storage. The degree and nature of the colour change was somewhat dependent on the year, the rate of 2,4-D applied and the cultivar. The change in tuber appearance arising from the 2,4-D treatments was not always considered desirable by consumer panellists. The 2,4-D treatments also reduced tuber damage by common scab (*Streptomyces scabies*), but tended to increase grade out to powdery scab (*Spongospora subterranea*). The ABA analogs had no consistent impact on yields, skin colour or disease reaction.

Key words: 2,4-dichlorophenoxyacetic acid, abscisic acid, common scab, powdery scab, *Streptomyces scabies*, *Spongospora subterranea*

Waterer, D. 2010. **Incidence des régulateurs de croissance sur la couleur et la tavelure des pommes de terre rouges**. Can. J. Plant Sci. **90**: 745–753. On aimerait que les pommes de terre de consommation présentent une peau rouge foncé uniforme. Malheureusement, la couleur du populaire cultivar Norland varie et a tendance à pâlir durant le stockage. L'étude devait établir si on peut rehausser la couleur de la peau des pommes de terre rouges par application foliaire de l'herbicide semblable à l'auxine 2,4-D ou d'analogues durables de l'acide abscissique (ABA), une hormone naturelle. Lors des essais effectués sur le terrain de 2007 à 2009, l'auteur a appliqué les régulateurs de croissance au feuillage de plants de Norland et d'AC Peregrine Red (une nouvelle variété rouge foncé) au stade de la tubérisation. Bien qu'il modifie l'aspect du feuillage, le 2,4-D n'a pas d'impact sur le rendement ni sur la forme des tubercules, mais en diminue le calibre moyen. Les évaluations objectives et subjectives indiquent que le 2,4-D modifie la couleur de la peau des tubercules immédiatement après la récolte et après une période prolongée de conservation au froid. L'intensité et la nature du changement dépendent dans une certaine mesure de l'année, du taux d'application du 2,4-D et du cultivar. Les consommateurs faisant partie des jurys n'ont pas toujours jugé souhaitable le changement d'aspect résultant de l'application du 2,4-D. Le 2,4-D atténue aussi les dommages causés par la tavelure (*Streptomyces scabies*), mais a tendance à augmenter le nombre de tubercules rejetés en raison de la gale poudreuse (*Spongospora subterranea*). Les analogues de l'ABA n'ont pas d'impact uniforme sur le rendement, la couleur de la peau ou la réaction aux maladies de la pomme de terre.

Mots clés: Acide 2,4-dichlorophénoxyacétique, acide abscissique, tavelure, gale poudreuse, *Streptomyces scabies*, *Spongospora subterranea*

Skin colour is important in consumer acceptance of fresh market potatoes. Potatoes are available in a wide range of skin colours, with white, red and russet being predominant in different areas of North America. On the Canadian prairies, consumers favor red-skinned potatoes and growers consequently strive to create and maintain red skin colour during production, storage and marketing. Norland is the dominant red-skinned cultivar grown on the Canadian prairies. Norland is early maturing and produces moderately high yields of tubers with an acceptably red skin colour. However, the skin colour of Norland and other red or purple skinned cultivars varies as a function of the strain of seed planted [Canadian Food Inspection Agency (CFIA) 2010], growing conditions (Fults et al. 1950) and production practices (Long and Snapp 2004). Skin colour of Norland also tends to fade during storage (CFIA 2010). In 2002, AC Peregrine Red was released as an alternative to Norland, with its key attribute being that its skin colour is darker and more uniformly red than Norland, both at harvest and after storage (Lynch et al. 2001). While yields of AC Peregrine Red are equal to or

Abbreviations: **ABA**, abscisic acid; **PGR**, plant growth regulators

superior to Norland, it is later maturing and has a smaller average tuber size (Lynch et al. 2001; Waterer 2009). A major limitation to AC Peregine Red is that it is more susceptible to common scab (*Streptomyces scabies*) than Norland (Waterer 2009; CFIA 2010). This persistent soil-borne disease is widespread in potato fields worldwide (Loria et al. 1997). While common scab has little impact on crop vigour, yields or eating quality, the scab lesions reduce the visual appeal of the tubers (Loria et al. 1997). At present there are no crop production techniques or protection products that provide a significant degree of protection against common scab.

Application of the auxin-type plant growth regulator (PGR) 2,4-D (2,4-dichlorophenoxyacetic acid) to the foliage of the developing crop is licensed for use in the United States to enhance the skin colour of red-skinned potatoes (Fults et al. 1950; Nylund 1956; Rosen et al. 2009). The PMRA is presently considering the licensing of 2,4-D for colour enhancement in red-skinned potatoes in Canada. The general recommendation is to apply the 2,4-D when the flower buds are just beginning to show. This easily identified growth stage coincides with the stage at which the potato crop begins to set tubers. The 2,4-D treatment is repeated 2 wk later, effectively encompassing the typical period of tuber set.

Exposure to low temperatures is known to enhance the accumulation of the anthocyanins responsible for the red colour in crops like potatoes and grapes. Exposure of plants to low temperatures triggers the production and/or accumulation of a number of compounds, including the plant growth regulator abscisic acid (ABA). California grape growers have found that application of ABA can be used as a substitute for cold weather as a means for improving the red skin colour in their crop (Peppi et al. 2006; Cantin et al. 2007). Abrams et al. (1997) have developed a range of synthetic ABA analogs that have more powerful and longer lasting effects that standard ABA (Sharma et al. 2005, 2006).

This project was designed to test the potential efficacy of plant growth regulators as a means of enhancing skin colour of red-skinned potato cultivars.

MATERIALS AND METHODS

Trials were conducted from 2007 to 2009 at two research sites maintained by the University of Saskatchewan in Saskatoon, Saskatchewan. Site 1 (Main field) features a sandy loam, pH 7.8, EC <1 dS, with 4% organic matter. This field has previously been cropped to potatoes three times in a 3-yr rotation with barley. Scab pressure at this site is low. Site 2 (Scab field) is also a sandy loam, pH 7.1, EC 1.1 dS, with 6% organic matter. This site was in a potato:barley:barley rotation for >30 yr but has been continuously cropped to potatoes for the past 6 yr in order to create a scab nursery. The site is heavily infested with both common scab (*Streptomyces scabies*) and powdery scab (*Spongospora subterranea*).

The trials were conducted utilizing standard potato production practices. The fields were fertilized prior to planting according to industry recommendations based on soil tests. The trials were planted in mid-May using cut certified Norland and AC Peregrine Red seed, with the seed pieces spaced 20 cm apart in the row, with 1 m between rows. The trials were laid out in a randomized complete block design ($N=3$ in 2007 and $N=4$ in 2008 and 2009). Each treatment row was 8 m long. The crop was hilled prior to emergence and again just prior to row closure. Weeds were controlled by tillage and the application of pre and post-emergent herbicides. An overhead irrigation system was employed whenever soil moisture potentials dropped below -50 kPa.

The timing of application of the 2,4-D and the rates applied were based on label recommendations as well as previous research (Waterer and Bantle 1998). The first application was made as the flower buds were just beginning to form, and the second application occurred 10 d later, at which time both cultivars were in full bloom. The PGRs were applied prior to 1000 utilizing a CO_2 powered small plot sprayer equipped with 80-02 flat fan nozzles. The sprays were applied in the equivalent of 200 L water ha^{-1}, which allowed thorough coverage of the leaves. The crop was not watered for at least 3 d after application of the PGRs and there were no rain events within 24 h of treatment.

The PGR treatments tested in 2007 were: (1) 2,4-D (low volatility ester formulation with 700 g a.i. L^{-1}) applied at the label recommended rate of 185 mL product ha^{-1}. (2) ABA analog – PBI 365 (8′ methylene methyl-ester ABA) is a longer-lasting and more potent analog of naturally occurring ABA (Abrams et al. 1997). The PBI 365 was applied at 10^{-4} M concentration. In previous studies with other horticultural crops, this concentration of PBI 365 had closed the stomata, thereby slowing crop water use and enhancing drought stress tolerance (Sharma et al. 2005, 2006). (3) Control – sprayed with water alone.

The PGR treatments tested in 2008 and 2009 were: (1) 2,4-D at the recommended rate of 185 mL product ha^{-1}. (2) 2,4-D at double the recommended rate (370 mL product ha^{-1}). This heavier dosage was used to determine if the effects of 2,4-D were dosage dependent. (3) ABA analog – PBI 365 applied at 10^{-4} M concentration. (4) ABA analog – PBI 429 (8′ acetylene methyl-ester ABA) applied at 10^{-4} M. Sharma et al. (2006) demonstrated that PBI 429 had even more long lasting ABA effects than PBI 365, but it often proved too potent, causing dwarfing and damage to the crop in a dosage dependent manner. (5) Control – sprayed with water alone.

Crop health status was monitored both prior to and after the spray events. In early September the plots were chemically desiccated and then machine harvested 3 wk later. The harvested tubers were held in a darkened 15°C storage for 2 wk to cure any wounds incurred during harvest. The crop was weighed, graded and then moved

to a darkened 8°C storage to simulate standard early season storage conditions for table potatoes.

After 6 wk of cold storage, 25 potatoes randomly chosen from each treatment replicate of each cultivar were washed and their skin colour was evaluated both visually and using a colorimeter (HunterLab MiniScan, Reston, VA). The visual assessment involved having trained panellists ($N = 20$) ranking the samples (most to least) for relative degree of red colour. The colorimeter was used to measure the CIE L, a, b values for each tuber. The L^*a^*b space describes colours by their position along three axes in 3D colour space. The L axis represents the lightness or brightness of the image and is a measurement of the white-to-black content of any colour. L values run from 0 (all black) to 100 (all white). The a axis runs from red to green with a range from -128 (green) to 127 (red). The b axis runs from yellow to blue with a range from -128 (blue) to 127 (yellow). Hue angle (arctan b/a) values measured the ratio of red-green hues against yellow-blue hues.

To assess the impact of PGRs applied during the growing period on the retention of skin colour during long-term cold storage the tubers used to assess skin colour at 6 wk after harvest were moved to standard cold storage (4°C and 95% RH) and held under those conditions for 4–5 mo. The colorimeter was used as previously described to provide an objective assessment of skin colour after this extended storage. The stored tubers were also ranked by panellists for the relative degree of red in the skin colour and as to which treatment the panellists would be "most to least interested in purchasing". The "willingness to purchase" ranking was designed to test whether the PGR treatments were altering the colour in a manner that consumers would actually find appealing. It also had the potential to highlight any effects the PGR treatments might have had on other characteristics that influence the decision to purchase – like tuber shape and size.

The impact of the PGR treatments on potato health was evaluated by visually examining 25 randomly selected tubers from all treatment replicates grown each year in the scab field. The proportion of the tubers that would have been rendered unmarketable due to excessive levels of either common or powdery scab was determined based on Canadian Food Inspection Agency (CFIA 1999) and United States Department of Agriculture (USDA 2008) standards, which stipulate that table potatoes no longer meet No.1 grade standards if more than 5% of the surface area is affected by diseases such as scab. The presence of cystosori was used to differentiated between lesions caused by powdery scab versus similar appearing lesions caused by common scab (Harrison et al. 1997).

Yield, colour and disease data were analyzed using PROC MIXED of SAS Institute, Inc. (2003) software, with field sites and PGR treatments as fixed effects and years and replicates (year) as random effects. All percentage data were normalized by arcsine square root transformation and then back-transformed for presentation. Mean comparisons were conducted using Fisher's protected LSD test ($P < 0.05$). Kruskal-Wallis tests were used to analyze the ranked data from the panel assessments.

RESULTS

Growing Conditions

2007

Temperatures during May and June of 2007 were cooler than average, July was exceptionally warm, whereas temperatures in August and September were near average. About 25 cm of rainfall was received during the 2007 growing season (average = 17 cm). This rainfall was supplemented with about 15 cm of irrigation, for a total of 40 cm of water.

2008

Temperatures were below normal in May and June of 2008, near average in July and August and above average through the harvest period in September. About 22 cm of rainfall was received during the growing season, with the irrigation system used to apply a further 15 cm for a total of 37 cm of water.

2009

Temperatures in May and June of 2009 were well below normal, slightly below average in July and August and well above average during the harvest period in September. About 23 cm of rainfall was received during the 2009 growing season with the irrigation system used to apply an additional 15 cm for a total of 38 cm of water.

Crop Health

Typical effects of foliar application of an auxin-type herbicide were apparent in the 2,4-D treatments within 3 d of spray application – the upper leaves became twisted and cup shaped, while the petioles grew more quickly than normal giving the crop a leggy, spindly appearance. These symptoms persisted for at least 2 wk after the treatments were applied. There was no apparent relationship between the dosage of 2,4-D applied and the severity or duration of the symptoms described. There were no visually apparent effects of any of the ABA treatments. Applying similar concentrations of these ABA analogs to other crops had slowed growth and development (Sharma et al. 2005, 2006). Aside from the described PGR effects, crop health appeared normal in all trials.

Yield

None of the PGR treatments had a significant impact on yield of either cultivar in the 2007 trial (Table 1). In 2008, in the Main field, the high rate of 2,4-D reduced the yield of AC Peregrine Red relative to the untreated

Table 1. Influence of foliar-applied plant growth regulators on yields and average tuber size of Norland and AC Peregrine Red potatoes at two field locations from 2007 through 2009

	Norland					AC Peregrine Red				
	Main field			Scab field		Main field			Scab field	
	2007	2008	2009	2008	2009	2007	2008	2009	2008	2009
					Yield (t ha^{-1})					
Control	46.8*a*	48.8*a*	53.3*a*	47.9*a*	42.7*a*	54.0*a*	55.4*a*	46.0*c*	44.2*a*	45.7*cd*
2,4-D@185 mL ha^{-1}	53.6*a*	50.0*a*	55.9*a*	43.2*a*	45.8*a*	52.3*a*	47.1*ab*	48.5*bc*	36.2*a*	51.2*ab*
2,4-D@370 mL ha^{-1}	–	44.8*a*	52.9*a*	44.5*a*	37.4*b*	–	38.4*b*	49.8*bc*	36.1*a*	42.5*d*
PBI 365	49.9*a*	49.5*a*	50.0*a*	42.9*a*	42.9*a*	59.2*a*	49.9*ab*	56.4*a*	41.1*a*	54.0*a*
PBI 429	–	46.4*a*	54.0*a*	44.8*a*	43.9*a*	–	53.1*ab*	52.8*ab*	43.0*a*	48.6*bc*
					Tuber wt (g)					
Control	–	186*a*	198*ab*	164*a*	180*a*	–	126*ab*	190*a*	143*a*	170*a*
2,4-D@185 mL ha^{-1}	–	149*b*	185*bc*	143*b*	164*b*	–	103*bc*	171*b*	104*b*	145*bc*
2,4-D@370 mL ha^{-1}	–	140*c*	177*c*	140*b*	153*b*	–	95*c*	146*c*	109*b*	127*c*
PBI 365	–	168*ab*	205*a*	164*a*	183*a*	–	136*a*	191*a*	132*a*	160*ab*
PBI 429	–	168*ab*	198*ab*	162*a*	189*a*	–	130*a*	178*b*	140*a*	147*bc*

a–d Values within columns followed by the same letter are not significantly different based on Fisher's protected LSD test ($P < 0.05$).

control. Otherwise the PGR treatments had no impact on yield in 2008. In 2009 both ABA treatments increased the yield of AC Peregrine Red in the Main field relative to the control, while in the Scab field, the high rate of 2,4-D reduced the yield of both cultivars relative to the controls (Table 1). The 2,4-D treatments caused a consistent decrease in the average tuber size (Table 1), with no consistent association between the dosage applied and the degree of size change observed. Neither of the PGR treatments influenced tuber shape.

Tuber Colour at Harvest

Visual Assessment

Based on the visual assessments made at harvest, tubers harvested from plants treated with 2,4-D appeared to be a darker red colour than the controls in all 3 yr of testing (Table 2). The effects of 2,4-D on skin colour were more apparent in Norland than in the darker skinned AC Peregrine Red. The ABA treatments had no consistent impact on the visual assessments of skin colour over the 3 yr of testing. The ratings provided by the panellists were quite consistent, but are nonetheless subjective.

Colorimeter Assessment

The colorimeter provides a method of objectively evaluating colour. The coefficients of variation for the colorimeter assessments were typically less that 5%, indicating that the observed treatment effects on colour were relatively consistent from tuber to tuber and that the colorimeter readings were reproducible.

Although the skin colours of the two cultivars were clearly different, the colorimeter readings indicated that they generally responded in a similar manner to treatment with the PGRs, although the degree of response tended to be greater in Norland than in AC Peregrine Red.

The CIE *L* values are a measure of the darkness of the skin. In 2007, the PGR treated tubers were darker than the controls (Table 2). This effect was not statistically significant for the darker skinned AC Peregrine Red, but was significant in the Norland. In 2008 and 2009, treatment with 2,4-D again rendered the skins of both cultivars darker than the controls (Table 2). In both cultivars in 2008, treatment with PBI 365 appeared to lighten the skin colour versus the controls, while the PBI 429 treatment darkened the skin colour. In 2009, ABA treatments had no impact on how dark the skin was for either cultivar (Table 2).

The CIE *a* values measure the relative amounts of red versus green in the skin colour. None of the PGR treatments had any consistent impact on the *a* values of either cultivar over the 3 yr of testing (Table 2). The apparent lack of impact of the PGR treatments on the red aspects of the tuber skin colour ran contrary to the results obtained from the visual assessments.

The CIE *b* values measure the relative amounts of blue versus yellow in the skin colour. The 2,4-D treatments consistently increased the relative amount of blue in the tuber skin colour (lower *b* values) (Table 2), while the ABA treatments had little impact on this colour attribute.

Hue angle represents the balance between red/green and blue/yellow. A low hue angle represents a preponderance of red and blue tones in the skin colour, with this mixture appearing purple. In Norland, and to a lesser extent AC Peregrine Red, the 2,4-D treated tubers tended to have a lower hue angle (more purple colour) than the controls (Table 2). The ABA treatments had little impact on the hue angle values.

Table 2. Influence of foliar-applied plant growth regulators on skin colour attributes of recently Harvested Norland and AC Peregrine Red potatoes in 2007 through 2009

	Norland			AC Peregrine Red		
	2007	2007	2009	2007	2008	2009
			(Visual rank)[z]			
Control	1.0*c*	2.6*c*	2.0*b*	1.25*b*	2.4*b*	1.6*c*
2,4-D@185 mL ha^{-1}	2.75*a*	3.7*b*	4.1*a*	2.25*b*	4.0*a*	3.1*b*
2,4-D@370 mL ha^{-1}	–	4.4*a*	4.0*a*	–	4.2*a*	3.6*ab*
PBI 365	2.25*b*	2.3*c*	2.2*b*	2.50*a*	2.0*b*	2.8*b*
PBI 429	–	2.0*c*	2.7*b*	–	2.4*b*	3.9*a*
			(CIE L)			
Control	37.3*a*	32.3*bc*	39.7*a*	35.0*a*	34.1*a*	35.8*ab*
2,4-D@185 mL ha^{-1}	36.4*b*	30.6*d*	36.3*a*	34.6*a*	30.8*c*	35.5*ab*
2,4-D@370 mL ha^{-1}	–	31.5*c*	37.2*b*	–	32.5*b*	34.8*b*
PBI 365	36.8*ab*	34.1*a*	39.2*a*	34.7*a*	33.4*a*	35.5*ab*
PBI 429	–	33.1*b*	39.4*a*	–	32.4*b*	36.8*a*
			(CIE a)			
Control	11.2*a*	14.8*a*	14.1*b*	11.0*a*	14.4*bc*	15.2*a*
2,4-D@185 mL ha^{-1}	11.0*a*	14.1*ab*	13.7*b*	11.4*a*	14.0*c*	14.5*b*
2,4-D@370 mL ha^{-1}	–	13.9*bc*	15.0*a*	–	14.5*abc*	14.7*b*
PBI 365	11.9*a*	13.6*bc*	14.1*b*	11.3*a*	15.2*a*	15.6*a*
PBI 429	–	13.2*c*	14.5*ab*	–	15.1*ab*	15.3*a*
			(CIE b)			
Control	8.0*a*	6.6*a*	8.8*a*	7.1*a*	6.8*a*	6.9*a*
2,4-D@185 mL ha^{-1}	6.6*c*	5.4*b*	6.5*b*	6.1*c*	5.2*b*	6.3*b*
2,4-D@370 mL ha^{-1}	–	5.6*b*	6.7*b*	–	5.6*b*	6.3*b*
PBI 365	7.3*b*	6.5*a*	8.1*a*	6.6*b*	6.8*a*	7.4*a*
PBI 429	–	6.7*a*	8.5*a*	–	6.8*a*	7.1*a*
			(Hue angle)			
Control	0.63*a*	0.43*ab*	0.56*a*	0.56*a*	0.45*a*	0.42*a*
2,4-D@185 mL ha^{-1}	0.52*c*	0.37*c*	0.44*b*	0.51*b*	0.36*b*	0.41*a*
2,4-D@370 mL ha^{-1}	–	0.40*bc*	0.42*b*	–	0.40*b*	0.40*a*
PBI 365	0.57b	0.44*ab*	0.52*a*	0.51*b*	0.43*a*	0.44*a*
PBI 429	–	0.47*a*	0.53*a*	–	0.44*a*	0.44*a*

[z]Treatments ranked by panelists from most (5) to least (1) red ($n = 20$).
a–c For each colour variable, values within columns followed by the same letter are not significantly different based on Fisher's protected LSD test ($P < 0.05$).

Tuber Colour after Storage

The potatoes showed minimal sprouting, dehydration or disease after 4–5 mo of cold storage over the winters of 2008/2009 and 2009/2010. The changes in skin colour during storage as assessed by the colorimeter were fairly consistent for the two cultivars for the 2 yr of testing. Both cultivars became slightly lighter (higher *L* value), with less red (lower *a* values) in the skin colour during storage (Table 3). The hue angle values consistently increased during storage, suggesting a shift from blue/red towards a more yellow/green tone in the skin colour.

When colours were assessed at harvest, treatment with 2,4-D had not consistently altered the *a* values, but had decreased the *L*, *b* and hue angle values of both cultivars, indicating that the skins were darker and more reddish-blue than the controls (Table 2). These effects persisted through the cold storage period in both years of testing (Table 3). The ABA treatments had little impact on colour either at harvest or after storage. The panellists also consistently picked the 2,4-D treated potatoes as having a darker red colour than the controls following cold storage in 2008/2009 (Table 3). This same treatment response was seen in Norland after cold storage in 2009/2010, but in AC Peregrine Red the non-treated control tubers were considered by the panellists to have the darkest red colour. This finding did not correspond with the colorimeter results (Table 3) in which various aspects of the colour (*L*, *b* and hue values) of the 2,4-D treated AC Peregrine Red tubers suggested a darker skin colour than the other treatments, including the control.

No one treatment emerged as superior to the others based on the consumer choice panels conducted after extended cold storage of the PGR treated potatoes in 2008/2009 and 2009/2010. For AC Peregrine Red, the majority of panellists preferred the PBI 429 treated potatoes in 2008/2009 and the control potatoes in 2009/2010, despite the fact that both the objective and subjective colour assessments rated these treatments as either equal or inferior to the 2,4-D treatments. For Norland, the PBI 365 treatment was preferred in 2008/2009 whereas in 2009/2010 the 2,4-D treatments

Table 3. Influence of foliar-applied plant growth regulators on skin colour attributes and consumer preference for Norland and AC Peregrine Red potatoes after 4 mo cold storage in 2008/2009 and 2009/2010

	Norland		AC Peregrine Red	
	2008/09	2009/10	2008/09	2009/10
		(CIE L)		
Control	34.4*a*	40.2*a*	35.1*a*	38.1*a*
2,4-D@185 mL ha^{-1}	34.2*a*	39.4*ab*	34.0*b*	37.2*b*
2,4-D@370 mL ha^{-1}	33.2*b*	38.6*b*	34.1*b*	36.6*c*
PBI 365	35.0*a*	40.7*a*	34.4*b*	38.0*a*
PBI 429	34.6*a*	40.0*a*	34.4*b*	38.1*a*
		(CIE a)		
Control	12.0*a*	12.3*b*	12.6*a*	13.2b
2,4-D@185 mL ha^{-1}	12.2*a*	12.1*b*	12.7*a*	13.5*b*
2,4-D@370 mL ha^{-1}	11.5*a*	13.1*a*	12.2*a*	12.9c
PBI 365	12.2*a*	12.5*b*	12.4*a*	14.0*a*
PBI 429	11.9*a*	12.3*b*	12.5*a*	14.2*a*
		(CIE b)		
Control	6.8*ab*	9.0*a*	7.1*a*	3.9*a*
2,4-D@185 mL ha^{-1}	6.0*c*	7.2*b*	5.9*c*	3.4*b*
2,4-D@370 mL ha^{-1}	5.9*c*	6.5*b*	6.3*b*	3.1*b*
PBI 365	6.6*b*	8.3*a*	6.9*a*	3.8*a*
PBI 429	7.1*a*	8.9*a*	7.0*a*	3.8*a*
		(Hue angle)		
Control	0.53*a*	0.63*a*	0.52*a*	0.50*a*
2,4-D@185 mL ha^{-1}	0.46*c*	0.55*ab*	0.44*c*	0.44*b*
2,4-D@370 mL ha^{-1}	0.47*c*	0.47*b*	0.48*b*	0.42*b*
PBI 365	0.50*b*	0.59*a*	0.51*a*	0.48*a*
PBI 429	0.54*a*	0.63*a*	0.52*a*	0.47*a*
		(Visual rank)[z]		
Control	1.6*d*	2.2*b*	2.1*b*	3.8*a*
2,4-D@185 mL ha^{-1}	5.0*a*	4.4*a*	4.6*a*	3.6*a*
2,4-D@370 mL ha^{-1}	3.7*b*	4.3*a*	4.4*a*	3.1*b*
PBI 365	2.5*c*	2.1*b*	2.0*b*	2.7*b*
PBI 429	2.2*c*	2.0*b*	1.9*b*	1.8*c*
		(Purchase preference)[y]		
Control	0	0	25	70
2,4-D@185 mL ha^{-1}	45	20	10	0
2,4-D@370 mL ha^{-1}	4	70	5	0
PBI 365	50	5	0	25
PBI 429	0	5	60	5

[z]Treatments ranked by panelists from most (5) to least (1) red ($n = 20$).
[y]Proportion of the panelists "most willing to purchase" each treatment ($n = 20$).
a–c For each variable, values within columns followed by the same letter are not significantly different based on Fisher's protected LSD test ($P < 0.05$).

were considered superior. These results suggest that while colour may be an important selection criterion for tuber quality, other aspects of tuber appearance may also influence consumer preference.

Disease

Heavy scab pressure at the nursery site resulted in extensive grade out to common and powdery scab in both years of testing. As expected, grade out due to common scab was more of a problem for AC Peregrine Red than for the more resistant Norland. The two cultivars appeared to have a comparable level of sensitivity to powdery scab. In 2008, common scab was rare in the Norland crop irrespective of the PGR treatments (Table 4). In AC Peregrine Red, the 2,4-D treatments dramatically reduced grade out to common scab. The degree of mitigation of the common scab problem was not related to the rate of 2,4-D applied. While the 2,4-D treatments reduced common scab on AC Peregrine Red, they appeared to increase grade out due to powdery scab in both cultivars. Neither of the ABA analogues had any impact on levels of either common or powdery scab in 2008 (Table 4).

In the 2009 trial, foliar application of 2,4-D reduced grade out to excess common scab in both cultivars as compared with the controls (Table 4). The degree of mitigation of common scab damage was again not related to the rate of 2,4-D applied. Both ABA analog treatments increased grade out of AC Peregrine Red to excess common scab. In Norland, both levels of 2,4-D increased grade out due to powdery scab, but in AC Peregrine Red the 2,4-D treatments had no impact on losses to this disease. Treatment with PBI 429 resulted in a significant reduction in grade out to powdery scab in AC Peregrine Red in 2009.

DISCUSSION

The impact of the PGR treatments on yields, crop colour and levels of disease showed significant variability from cultivar to cultivar and from year to year. This is not surprising given the potential complexity of interactions between environmental conditions, crop growth patterns, pathogen activity and efficacy of any applied treatment. There nonetheless appeared to be some consistent trends in the crop response to the PGR treatments. When applied at the label recommended rates, foliar applications of 2,4-D altered the growth habit of the potato crop, but had little impact on yield. Higher dosages tended to reduce yields, an effect noted by other researchers (Macintosh et al 1981, 1982; Rosen et al. 2009). The 2,4-D treatments appeared to increase the number of tubers set per plant, resulting in a

Table 4. Influence of foliar-applied plant growth regulators on grade out due to excess common or powdery scab for Norland and AC Peregrine Red potatoes in 2008 and 2009

	Norland				AC Peregrine Red			
	Common scab		Powdery scab		Common scab		Powdery scab	
	2008	2009	2008	2009	2008	2009	2008	2009
Control	3*a*	11*a*	15*b*	50*b*	63*a*	38*b*	20*c*	60*a*
2,4-D@185 mL ha^{-1}	0*a*	0*b*	28*ab*	74*a*	2*b*	20*c*	58*a*	61*a*
2,4-D@370 mL ha^{-1}	0*a*	0*b*	37*a*	79*a*	3*b*	22*c*	42*b*	64*a*
PBI 365	1*a*	0*b*	24*ab*	49*b*	61*a*	59*a*	22*c*	64*a*
PBI 429	3*a*	8*a*	16*b*	54*b*	61*a*	65*a*	28*c*	37*b*

a–c Values within columns followed by the same letter are not significantly different based on Fisher's protected LSD test ($P < 0.05$).

significant reduction in average tuber size. This treatment effect has been reported previously (Fults et al. 1950; MacIntosh et al. 1981) and is noted on the product label.

Based on both panel assessments and colorimeter data the 2,4-D treatments appeared to alter the skin colour of both cultivars at the time of harvest and this effect persisted through months of cold storage. The colorimeter data indicate that the colour change involved a general darkening of the skin (lower *L* values), with an increase in the amount of blue tones (lower *b* values) in the skin, but with a limited effect on the amount of red (*a* values) in the skin colour. The change in balance between the various primary colours in the skin was reflected by changes in the hue values, which indicated a shift to more red/blue relative to yellow/green. Rosen et al. (2009) found a similar change in *L* and hue angle values for Norland treated with 2,4-D. They found that the 2,4-D treatments reduced levels of the red anthocyanin-type pigment pelargonidin (lower *a* values) with a corresponding increase in the levels of the red-blue peonidin anthocyanin (higher *b* and hue angle values). While the 2,4-D treated tubers were clearly darker and more purplish red than the non-treated tubers, the 2,4-D treated tubers were not consistently chosen as having enhanced consumer appeal. This suggests that either this type of colour change was not desirable or that some factors other than skin colour were influencing consumer preferences. Consumer appeal involves a complex blend of selection criteria, many of which are highly subjective. If the PGR treatments were negatively affecting some aspect of tuber appearance, this may supersede any effects enhancing skin colour. We did not observe any obvious treatment effects on tuber conformation beyond the previously noted reduction in the average tuber size in the 2,4-D treatments. The change in tuber size would have had no impact on commercial grading standards for the crop, but might have been subtly influenced the panellists' choice preferences. It is noteworthy that while the 2,4-D treatments enhanced the colour of both cultivars, the colour change induced by the 2,4-D treatments was less frequently favoured in AC Peregrine Red than in Norland. This may reflect the fact that AC Peregrine Red is inherently a deeper shade of red than Norland (Lynch et al. 2001). The average tuber size of AC Peregrine Red is also smaller than that of Norland (Lynch et al. 2001). It is therefore possible that the 2,4-D treatments were reducing the size of the AC Peregrine Red tubers below some ''acceptance threshold'' while the larger Norland tubers remained above this threshold. A reduction in the average tuber size without sacrificing yields might be desirable for seed potato production; however, concerns about potential carry-over effects has limited the use of PGRs like 2,4-D in seed potatoes.

Although application of ABA has been used to enhance anthocyanin production in a range of crops, the ABA analog treatments used in this project did not have any consistent impact on the colour of the red-skinned potato cultivars tested. Rosen et al. (2009) found a similar lack of response when standard ABA was applied to the foliage of Norland potatoes. The lack of response may reflect the use of an insufficient dosage; however, the concentrations applied in this project had produced obvious, long-lasting changes in the growth and stress tolerance of other crops (Sharma et al. 2005, 2006).

Treatment of the foliage with 2,4-D appeared to reduce the severity of tuber damage by common scab (*Streptomyces scabies*). There have been several previous reports of foliar applied 2,4-D (or similar auxin-like herbicides) reducing levels of common scab in potato. MacIntosh et al. (1981) showed that foliar application of a range of different phenoxy-type auxin analog herbicides reduced common scab, but the treatments that were most effective also reduced yields and altered tuber shape and size distribution. As they found that 2,4-D was not directly effective at controlling growth of the scab organism in pure culture, they speculated that the 2,4-D was instead rendering the potato tubers more resistant to the pathogen. In subsequent field studies Macintosh et al. (1982) tested a range of concentrations and formulations of 2,4-D for scab control but found in every case that treatments that provided an effective level of disease suppression also reduced yields and/or crop quality to an unacceptable degree. They speculated that the 2,4-D may be acting as a growth suppressant, thereby rendering the potatoes more resistant to scab. They suggested that other growth suppressants, like ABA and daminozide, should be evaluated as potential scab control agents. However in this project ABA appeared to provide little in the way of scab control, but, as noted previously, the dosages used may have been insufficient for potatoes. While MacIntosh and Bateman (1979) showed that foliar applied daminozide reduced tuber infection by common scab in greenhouse trials, Waterer (1998) found no consistent impact on scab levels when daminozide was applied in field trials. Tegg et al. (2008) showed that 2,4-D treatments had no impact on tuber anatomy (i.e., lenticel numbers, lenticel external dimensions, periderm thickness or structure) that could explain the apparent change in resistance to common scab. They instead suggested that the 2,4-D treatment may increase the tubers' tolerance to the thaxtomin A toxin produced by the scab organism. The corky skin lesions characteristic of common scab are a product of the potatoes' immune response to this toxin (Loria et al. 1997).

Although treatment with 2,4-D appeared to reduce damage by common scab, there was a corresponding but weaker trend for the 2,4-D treatments to increase the severity of damage by powdery scab (*Spongospora subterranea*). The balance between levels of tuber infection by common versus powdery scab can be influenced by host genetics (Harrison et al. 1997;

Waterer 2009) and growing conditions, especially soil temperature (Harrison et al. 1997; Loria et al. 1997) and moisture levels (Lapwood and Hering 1970; Taylor et al. 1986). The 2,4-D treatments had no obvious effects on crop growth that could explain the apparent shift in the relative sensitivity of the crop to common versus powdery scab. It is unlikely that the altered sensitivity to common versus powdery scab is linked to the effect that 2,4-D exerted on skin colour. While AC Peregrine Red is darker red than Norland it is also more susceptible to common scab (Lynch et al. 2001; Waterer 2009). MacIntosh et al. (1981, 1982) and Tegg et al. (2008) also showed that application of 2,4-D reduced common scab damage without altering the colour of white-skinned potatoes. It is possible that the observed increase in powdery scab following application of 2,4-D is reflecting an opportunistic invasion of an infection field that has been freed from competition by another pathogen. *Streptomyces* species are renowned for production of a wide range of antibiotics that assist it to compete for space in an infection field (Goodfellow et al. 1988). While the lesions of common and powdery scab are similar in appearance, the pathogens and the host/pathogen interactions are very different. One obvious difference is that powdery scab does not produce an exotoxin like thaxtomin. This difference in toxicity mechanisms may explain why the 2,4-D treatments that suppressed common scab had no corresponding beneficial effect on infection by powdery scab. However, Tegg et al. (2008) found little impact of 2,4-D treatments on thaxtomin production by cultures of *Streptomyces*.

SUMMARY

Field trials conducted from 2007 to 2009 suggest that appropriate rates of foliar applied 2,4-D can enhance the colour of commonly grown red-skinned potato cultivars with minimal risk of negative impact on crop vigour, yields or tuber quality. The nature and extent of colour change achieved by applying the 2,4-D was influenced by growing conditions and the cultivar being treated. The 2,4-D treatments also appeared to protect the tubers from common scab, but could increase damage by powdery scab. From a grower's perspective the type of scab causing a tuber to be culled is of limited initial importance. If, however, 2,4-D treatments are widely adopted as a tool for enhancing tuber colour, the tendency of these treatments to suppress tuber infection by common scab while favouring infection by powdery scab may cause a shift in scab populations. While common scab is ubiquitous in soils across North America (Loria et al. 1997), powdery scab is presently more localized. Adoption of 2,4-D treatments may have only limited net benefit at reducing losses to scab at sites where both types of scab are already endemic, but they should reduce losses at the sites where only common scab is found. Similarly, dry land growers may see greater benefit from the apparent disease control provided by the 2,4-D treatments, as drought stressed conditions tend to favour common rather than powdery scab (Lapwood and Hering 1970). Conversely, irrigated growers interested in improving crop colour should be careful as the 2,4-D treatments appear to have the potential to exacerbate the issues with powdery scab that are already more prevalent at wetter sites (Taylor et al. 1986).

PMRA is presently reviewing performance and crop residue data to determine whether 2,4-D treatments should be approved as a tool for enhancing skin colour of red-skinned potatoes in Canada. The results of these trials have been supplied to PMRA. The potential for the 2,4-D treatments to alter the disease sensitivity of the crop may be of interest in these considerations.

ACKNOWLEDGEMENTS

This research was supported by the Agriculture Development Fund of Saskatchewan Agriculture.

Abrams, S. R., Rose, P. A., Cutler, A. J., Balsevich, J. J. and Walker-Simmons, M. J. 1997. 8′ Methylene ABA: An effective and persistent analog of abscisic acid. Plant Physiol. **144**: 89–87.

Cantin, C., Fidelibus, M. W. and Crisosto, C. H. 2007. Application of abscisic acid (ABA) at veraison advanced red colour development and maintained post-harvest quality of "Crimson Seedless" grapes. Postharv. Biol. Technol. **46**: 237–241.

Canadian Food Inspection Agency. 1999. Inspection manual for potatoes [Online] Available: http://www.inspection.gc.ca/english/fssa/vegleg/potpom/1-6e.shtml [2010 Mar. 1].

Canadian Food Inspection Agency. **2010.** Potato varieties. Norland. [Online] Available: http://www.inspection.gc.ca/english/plaveg/potpom/var/norland/norlande.shtml. [2010 Mar. 1].

Fults, J. L., Schaal, L. A., Landblom, N. and Payne, M. G. 1950. Stabilization and intensification of red skin colour in Red McClure potatoes by the use of sodium salt of 2-4-dichlorphenoxyacetic acid. Am. Potato J. **27**: 377–395.

Goodfellow, M., Williams, S. T. and Mordarski, M. 1988. Actinomycetes in biotechnology. Academic Press, London, UK.

Harrison, J. G., Searle, R. J. and Williams, N. A. 1997. Powdery scab disease of potato – a review. Plant Pathol. **46**: 1–25.

Lapwood, D. H. and Hering, T. F. 1970. Soil moisture and the infection of young potato tubers by *Streptomyces scabies* (common scab). Potato Res. **13**: 296–304.

Long, C. and Snapp, S. 2004. Management profile for potato variety Michigan purple. [Online] Available: http://fieldcrop.msu.edu/documents/E2918.pdf [2010 Mar. 1].

Loria, R., Bukhalid, R. A., Fry, B. A. and King, R. K. 1997. Plant pathogenicity in the genus *Streptomyces*. Plant Dis. **81**: 836–846.

Lynch, D. R., Secor, G., Kawchuk, L. M., Waterer, D., Schaupmeyer, C. A., Holley, J., Fujimoto, D. K., Driedger, D., Wahab, J. and Goettel, M. S. 2001. AC Peregrine Red: A high-yielding red-skinned fresh market cultivar. Amer. J. Potato Res. **78**: 333–337.

McIntosh, A. H. and Bateman, G. L. 1979. Effects of foliar sprays of daminozide on the incidence of potato common scab. Ann. Appl. Biol. **92**: 29–38.

McIntosh, A. H., Bateman, G. L., Chamberlain, K., Dawson, G. W. and Burrell, M. M. 1981. Decreased severity of potato common scab after foliar sprays of 3,5-dichlorophenoxyacetic acid, a possible antipathogenic agent. Ann. Appl. Biol. **99**: 275–281.

McIntosh, A. H., Burrell, M. M. and Hawkins, J. H. 1982. Field trials of foliar sprays of 3,5-dichlorophenoxyacetic acid (3,5-D) against common scab on potatoes. Potato Res. **25**: 347–350.

Nylund, R. E. 1956. The use of 2,4-D to intensify skin colour of Pontiac potatoes. Amer. Potato J. **33**: 145–154.

Peppi, M. C., Fidelibus, M. W. and Dokoozlian, N. 2006. Abscisic acid application timing and concentration affect firmness, pigmentation and color of 'Flame Seedless' grapes. HortScience **41**: 1440–1445.

Rosen, C. J., Roessler, J. A., Petracek, J. D., Englemann, S. and Tong, C. S. 2009. 2,4-dichlorophenoxyacetic acid increases peonidin derivatives in red Norland periderm. Amer. J. Potato Res. **86**: 15–23.

SAS Institute, Inc. **2003.** SAS/STAT user's guide. SAS Institute, Inc., Cary, NC.

Sharma, N., Abrams, S. R. and Waterer, D. 2005. Abscisic acid analogs reduce transplant shock in tomato seedlings. J. Veg. Sci. **11**: 41–56.

Sharma, N., Abrams, S. R. and Waterer, D. R. 2006. Evaluation of abscisic acid analogs as holding agents for bedding plant seedlings. HortTechnology **16**: 71–77.

Taylor, P. A., Flett, S. P., de Boer, R. F. and Marshall, D. 1986. Effects of irrigation regime on powdery scab diseases and yield of potatoes. Austr. J. Exp. Agric. **26**: 745–750.

Tegg, R. S., Gill, W. M., Thompson, H. K., Davies, N. W., Ross, J. J. and Wilson, C. R. 2008. Auxin-induced resistance to common scab disease of potato linked to inhibition of thaxtomin A toxicity. Plant Dis. **92**: 1321–1328.

United States Department of Agriculture. **2008.** United States standards for grades of potatoes. [Online] Available: http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5068888 [2010 Mar. 01].

Waterer, D. **1998.** Canopy management to control common scab. [Online] Available: http://www.usask.ca/agriculture/plantsci/vegetable/potato/ppestmgmt.htm#IntegratedCropManagement3 [2010 Mar. 01].

Waterer, D. and Bantle, J. 1998. Impact of low dosage foliar applied 2,4-D on skin color of red potatoes. [Online] Available: http://www.usask.ca/agriculture/plantsci/vegetable/resources/potato/1998_24D.pdf [2010 Mar. 01].

Waterer, D. 2009. Potato variety trials – longterm average data. [Online] Available: http://www.usask.ca/agriculture/plantsci/vegetable/potato/pvarietytrials.htm [2010 Mar. 01].

This article has been cited by:

1. Michael K. Thornton, Jungmin Lee, Robin John, Nora L. Olsen, Duroy A. Navarre. 2013. Influence of Growth Regulators on Plant Growth, Yield, and Skin Color of Specialty Potatoes. *American Journal of Potato Research* **90**:3, 271-283. [CrossRef]
2. Robert S. Tegg, Ross Corkrey, Calum R. Wilson. 2012. Relationship Between the Application of Foliar Chemicals to Reduce Common Scab Disease of Potato and Correlation with Thaxtomin A Toxicity. *Plant Disease* **96**:1, 97-103. [CrossRef]
3. Doug Waterer, Hanny Elsadr, Mary-Lee McArthur. 2011. Skin Color, Scab Sensitivity and Field Performance of Lines Derived from Spontaneous Chimeras of Red Norland Potato. *American Journal of Potato Research* **88**:3, 199-206. [CrossRef]