Interim Report

Maleic hydrazide optimization as a sprout suppressant

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1. SUMMARY

1.1. Aim

To identify practices in maleic hydrazide (MH) application which increase tuber uptake of MH and provide more consistent sprout suppression in storage.

1.2. Methodology

Five trials were carried out to assess potential causes of variability in tuber MH concentration:

- Between-plant variation at different levels of applied MH from 0 to 200 % of the label recommended application (Trial 1)
- Varying the timing of MH application from 6am to 12pm and 6pm (Trial 2)
- Varying water volume when applying MH between 180 and 540 l/ha (Trial 3)
- Including the adjuvant Ranman Top with MH in the tank mix (Trial 4)
- Variety determinacy and canopy cover at MH application, comparing MH uptake and sprouting control between Innovator, Lady Claire, Maris Piper and Royal (Trial 5)

Tubers MH residues were quantified shortly after harvest, then tubers were stored at 9 °C for 5 months after which the efficacy of sprout suppression was assessed, recording the weight of sprouts produced and length of the longest sprout.

1.3. Key findings

MH residues remain variable between individual plants and tubers, and sprout suppression is least effective in smaller tubers. Sprout suppression was more effective following MH applications either early or late in the day, compared to applications at midday. Neither water volume, nor the presence of an adjuvant during application had any effect on either MH levels or sprout suppression in store. Split applications of MH may help increase MH uptake, however further experiments are required to confirm and then optimise this. The timing of MH application should be managed with regard to variety, particularly considering canopy maturity at application.

1.4. Practical recommendations

- Avoid applying MH at midday, early morning or early evening applications provide better sprout control. Though differences in humidity between days may be greater than within a day so selecting a humid day remains important.
- Applying MH can be applied with Ranman Top without a reducing MH uptake, though higher water volumes used should be used (according to the MH, not the Ranman Top label) as lower water volumes may reduce MH uptake.

- Assess timing for MH application on a varietal basis, adjusting timing with respect to expected canopy duration as indicated by determinacy group.
- Separate small tubers (<60 g) from the rest of the crop before storage to avoid the need to apply in-store sprout suppressants solely for the small tubers which have begun to sprout when sprouting is still adequately controlled in the medium to large tubers.

2. INTRODUCTION

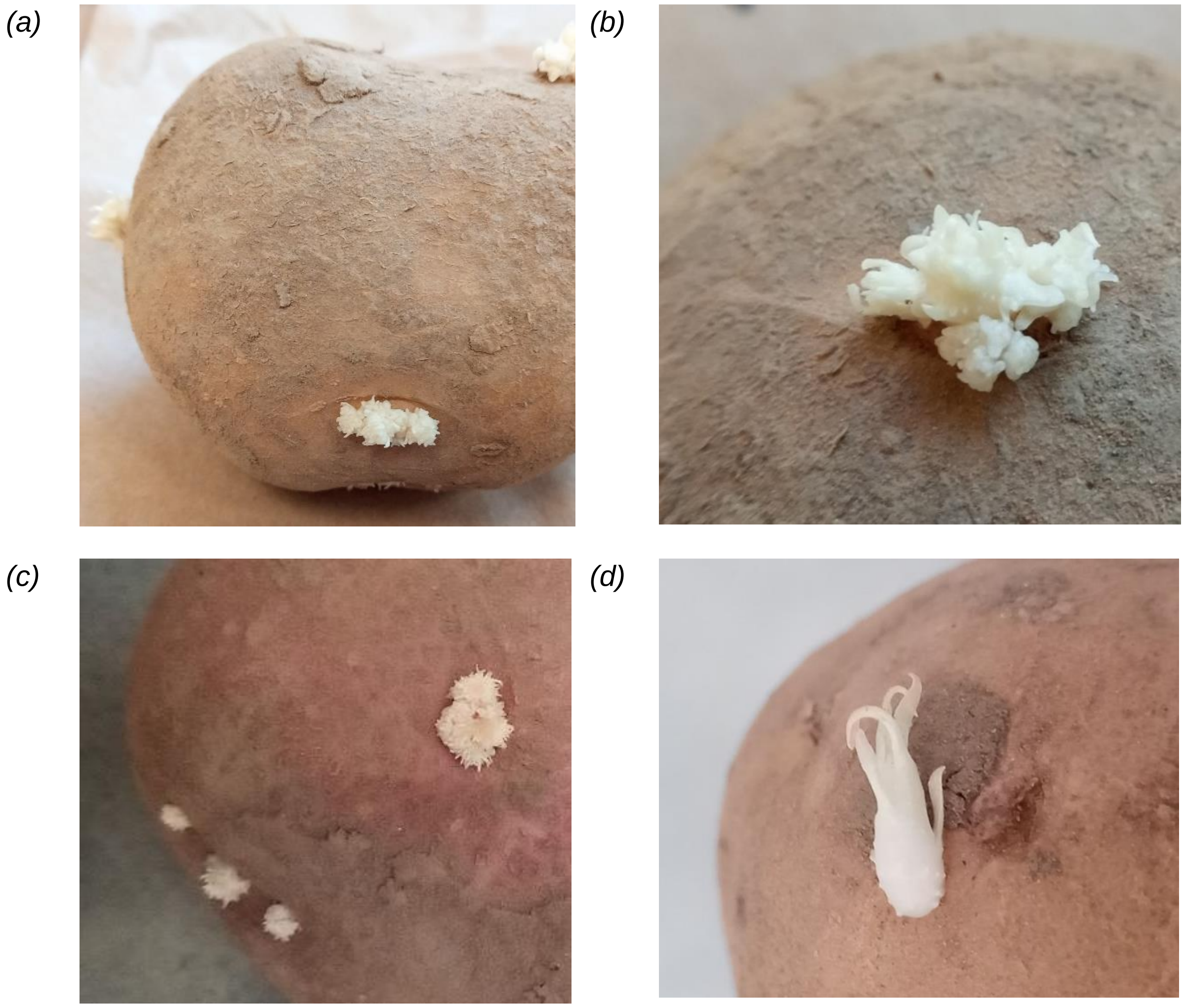
Maleic hydrazide (MH) has been registered as a growth regulator in the UK since the 1980's. It has a range of crop and non-crop uses and it is authorised for use in sprout suppression of onion and potato and for volunteer control of potato in the UK. MH prevents cell division (Nooden 1969), disrupting sprout development in both stored tubers and volunteers (see examples in Figure 1). Since the non-renewal of CIPC (chlorpropham) in 2019 successful use of the remaining sprout suppressant products has become more important. This is especially so for MH because its non-volatile nature has the potential to reduce sprout growth over long storage durations with a single application in the field before crop canopy senescence (Briddon & Winmill 2021). In addition, the successful use of MH can have an important effect on the economics of potato storage. In many cases, should MH applications not be successful, larger volumes of relatively costly post-harvest treatments may be required to maintain sprout control during storage (Briddon & Winmill 2021).

Unfortunately, MH control of sprouting has been shown to be variable and so more research is needed to improve the guidance on MH applications. In this project MH application conditions were varied to identify key factors in maximising MH uptake and subsequent sprout suppression. Mean efficacy of sprout suppression increases with increasing MH tuber residues at a non-linear rate with *c.* 80 % sprout suppression achieved at 8 mg/kg, yet residues were highly variable between plants (Briddon *et al.* 2020). Variability of MH tuber residues was explored over a wider range of MH application rates in one of the 2021/22 experiments.

Previous work at SBCSR has shown that maintaining high humidity for 24 hours following MH application resulted in a three-fold increase in tuber MH levels relative to plants under drying conditions (Briddon & Winmill 2021). Whilst a 24 hour period of high humidity is unlikely to occur under agricultural conditions in the UK, this finding suggests that MH uptake is increased by prolonging the time which MH is in solution on the potato leaves and by maintaining leaf turgidity. An experiment was designed to compare the effect of applying MH at different times during the day, with differing conditions. Additional experiments were also designed to test the best practice recommendations to apply MH with larger volumes of water (to maximise MH coverage throughout the canopy and slow drying, (Certis 2020; Demin 2021)) and without adjuvants (which may dry the leaf and reduce MH uptake, (Certis 2020; Demin 2021)).

Lastly, previous work indicated that MH uptake varies between variety (Newberry & Thornton 2007a; Briddon & Stroud 2021). Briddon and Stroud hypothesised that this variation may be linked to canopy size at the time of application. If so, then adjusting the planting dates of varieties from each determinacy group to achieve canopy maturity around the same calendar date should result in similar MH uptake across the determinacy groups and so a final experiment was planted to test this.

Figure 1. Examples of the effects of MH on potato sprout morphology in (a, b) Alcander and *(c, d)* Desiree



3. Materials and methods

Five trials were carried out at both SPot North (RJ & AE Godfrey Farms, Eastoft), and at SPot West (Gatley Farms, Leominster). At SPot North, Maris Piper was planted by Will Gagg, and at SPot West, Russet Burbank was planted on 5 May 2021, by James Oliver. Maleic hydrazide applications varied in rate (Trial 1), time of day (Trial 2), water volume used (Trial 3), adjuvant (Trial 4) and cultivar determinacy (Trial 5). MH was applied as Fazor, which contains 600 g/kg (60 % w/w) MH. The standard, or 100 %, application was 5 kg Fazor in 360 l/ha water, as per label recommendation. MH application treatments are described as a percentage of this standard application.

At Spot North, there was an additional and unintentional blanket application of MH (at 100 % of the recommended label rate), applied at the same time as the rest of the field which the trial was situated within, approximately one week before the experimental applications, hence results are shown separately for the two locations as they are not directly comparable

Five trials were carried out to assess potential causes of variability in tuber MH concentration including:

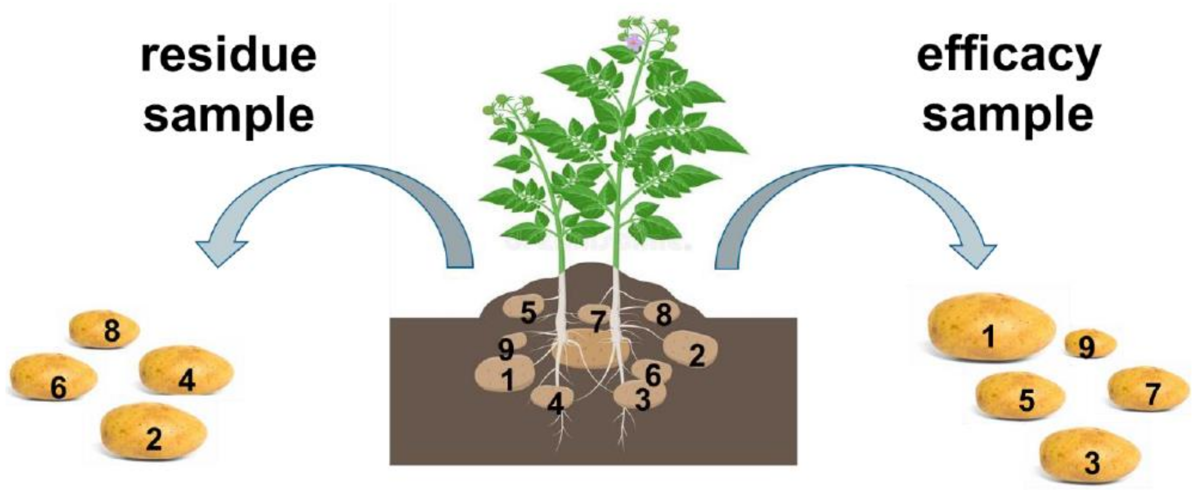
- Between-plant variation at different levels of applied MH (Trial 1)
- Varying the timing of MH application (Trial 2)
- Varying water volume when applying MH (Trial 3)
- Including an adjuvant with MH in the tank mix (Trial 4)
- Variety determinacy and canopy cover at MH application (Trial 5)

3.1. Trial 1 - Rate of MH application

Maleic hydrazide treatments were applied to unreplicated plots at four rates (25, 50, 100 and 200 % of 5 kg Fazor in 360 l/ha water) with a no MH control. Plots were 3 x 5 m at SPot North and 3.6 x 3 m at SPot West. MH was applied on 11 August 2021 between 10 and 11 am at SPot North and on 16 August at SPot West (precise timings unknown) when the crop was unstressed, under conditions of high humidity. Tubers >25 mm from 10 individual plants per plot were harvested separately by Richard Austin Associates at the end of September (SPot North) and Produce Solutions on 11 October (SPot West) and were delivered to NIAB for assessment on 1 and 15 October, respectively.

Tubers from each plant were divided into two sub-samples based on tuber size, ensuring a similar size distribution of tubers in each sample (Figure 2). The first sample was analysed for MH residue concentration by SGS Cambridge (Bar Hill, Cambridgeshire, CB23 8UD), and was quantified by liquid chromatography (LC MS-MS) following extraction from whole tubers using acidified methanol. The second sample was stored at 9 °C in trays, in paper sacks for 22 weeks (21 October to 28 March), then the efficacy of sprout control was quantified at the end of March by measuring sprout length, sprout weight and the desprouted weight of individual tubers. Relative sprout weight (mg/g) was calculated by dividing the total weight of sprouts produced by an individual tuber (mg) by tuber weight (g), indicating relative weight loss due to sprouting.

Figure 2. Diagram showing division of tubers from a single plant, based on tuber size, into sub-samples for maleic hydrazide residue and efficacy assessments. Tubers were sorted by size from largest to smallest and numbered accordingly. Odd numbered tubers were selected for the efficacy sample and even numbered tubers were selected for the residue sample.



3.2. Trial 2 - Timing of MH application

Maleic hydrazide was applied at 100 % label rate (5 kg Fazor in 360 l/ha water) to 3 x 5 m and 3.6 x 3 m plots at SPot North and SPot West, respectively, with three replicates. Applications were made at 12 pm, 6 am and 6 pm—representing conditions of low, medium and high humidity, respectively—under anticyclonic conditions with hot days and cooler nights resulting in might higher humidity at night than during the day. Tuber samples of *c.* 15 kg were dug on the same dates as Trial 1 and delivered to NIAB for assessment within the week. MH residue and sprouting efficacy samples of 12 and 25 tubers >40 mm, respectively, were taken and processed as in Trial 1.

3.3. Trial 3 - Water volume

Maleic hydrazide treatments were applied at 100 % label rate (5 kg Fazor) with 180, 360 and 540 l/ha of water to 3 x 5 m and 3.6 x 3 m plots at SPot North and SPot West, respectively, with three replicates. Treatments were applied between 12 pm and 2 pm to an unstressed crop. Tuber samples of *c.* 15 kg were dug on the same dates as Trial 1 and delivered to NIAB for assessment within the week. MH residue and sprouting efficacy samples of 12 and 25 tubers >40 mm, respectively, were taken and processed as in Trial 1.

3.4. Trial 4 - Adjuvant and tank mix

Maleic hydrazide treatments were applied at 100 % label rate (5 kg Fazor) with the fungicide Ranman Top (Belchim Crop Protection) in 200 l/ha of water (adjuvant A), with Ranman Top in 360 l/ha of water (adjuvant B) or without Ranman Top (no adjuvant). Plots were 3 x 5 m and 3.6 x 3 m plots at SPot North and SPot West, respectively, with three replicates. Tuber samples of *c.* 15 kg were dug on the same dates as Trial 1 and delivered to NIAB for assessment within the week. MH residue and sprouting efficacy samples of 12 and 25 tubers >40 mm, respectively, were taken and processed as in Trial 1.

3.5. Trial 5 - Variety determinacy

Varieties representing the different determinacy groups were planted on different dates to achieve similar states of canopy maturity and senescence at the end of the season when MH was due to be applied. Plots were 3.6 x 3 m and 3.6 x 2.5 m plots at SPot North and SPot West, respectively and there were three replicates. Crop4Sight modelled expected canopy longevity and calculated differential planting dates for each variety (Table 1 and Table 2). At SPot West early and late plantings of each variety were planted between 7 and 17 days apart (based on the Crop4Sight calculations). MH was applied on 11 and 16 August at SPot North and SPot West, respectively, at 100 % of the recommended label rate (5 kg Fazor in 360 l/ha water). Tuber samples of *c.* 15 kg were dug on the same date as Trial 1 and delivered to NIAB for assessment within the week. MH residue and sprouting efficacy samples of 12 and 25 tubers >40 mm, respectively, were taken and processed as in Trial 1.

Table 1. Staggered planting dates at SPot North

Variety	Determinacy group	Planting date
Innovator	1	10 June
Lady Claire	2	22 May
Maris Piper	3	3 May
Royal	4	21 April

Table 2. Staggered planting dates at SPot West, with early (E) and late (L) plantings of each variety

Variety	Determinacy group	Planting	Planting date
Innovator	1	E	18 June
		L	25 June
Lady Claire	2	E	1 June
		L	18 June
Maris Piper	3	E	17 May
		L	1 June
Royal	4	E	5 May
		L	17 May

3.6. Data analysis

Data analysis was carried out in R (R Core Team 2022) using RStudio version 2022.02.2.485 (RStudio Team 2022). Two-way ANOVA was used to compare treatments effects and Tukey's Honest Significant Difference test was used for post-hoc analysis.

4. RESULTS

4.1. SPot West

4.1.1. Trial 1

MH tuber residues increased with increasing concentration of the application (Figure 3), though above 100 % application rate increases in tuber residue were small and not proportional to the increased MH application. In the no MH treatment, five samples had a residue value <1.0 mg/kg (the detection limit), but the remainder had 1.1 to 4.7 mg/kg MH present, indicating that some drift occurred whilst spraying. Residues across all treatments were below 60 mg/kg, the maximum residue limit (MRL). Whilst the 100 % application treatment produced the lowest relative weight of sprouts (0.6 mg/kg, compared to mean 2.2 mg/kg across the other treatments, Figure 4), this difference was not significant at SPot West (ANOVA, $P = 0.056$).

Figure 3. Mean MH residue concentration in tubers following 0, 25, 50, 100 and 200 % applications of MH in Russet Burbank at SPot West. Error bars show S.E.

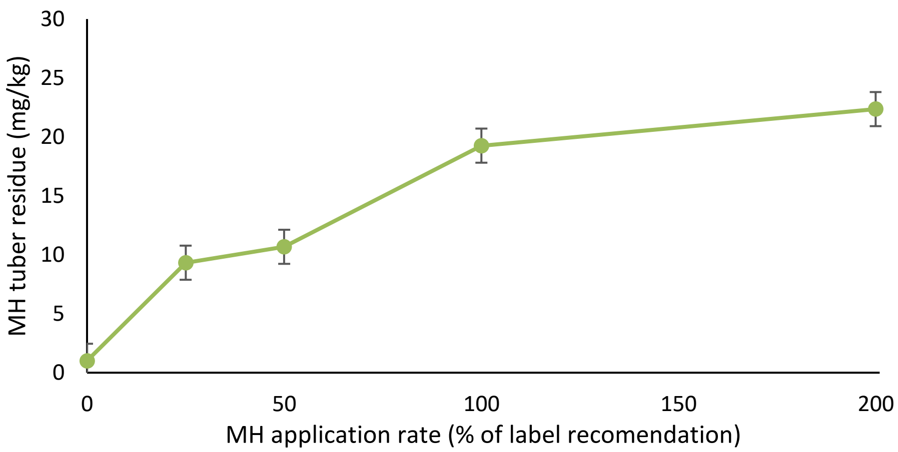
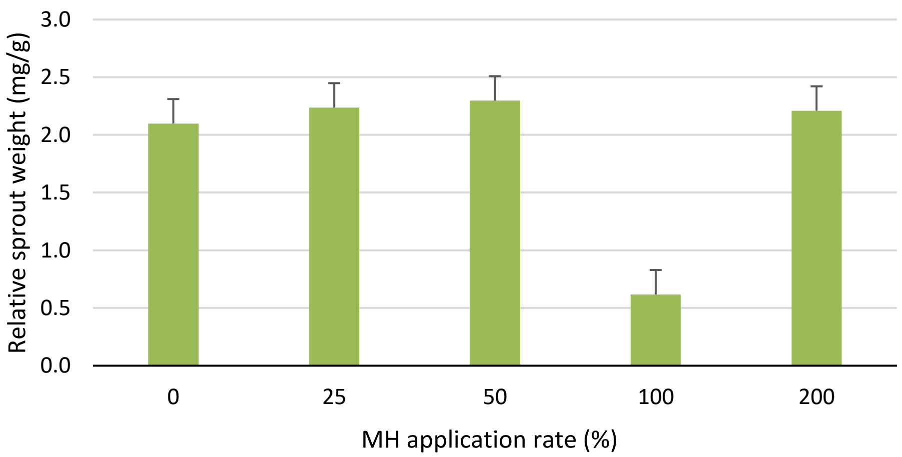


Figure 4. Relative sprout weight produced (mg sprouts/g tuber) following 0, 25, 50, 100 and 200 % applications of MH in Russet Burbank at SPot West. Error bars show S.E.

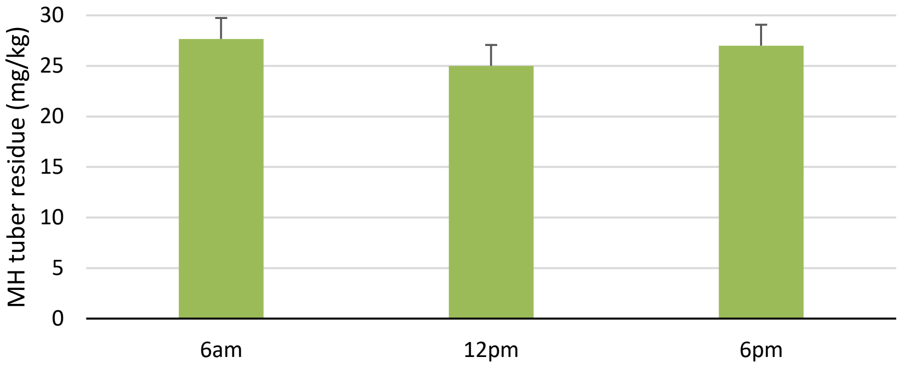


4.1.2. Trial 2

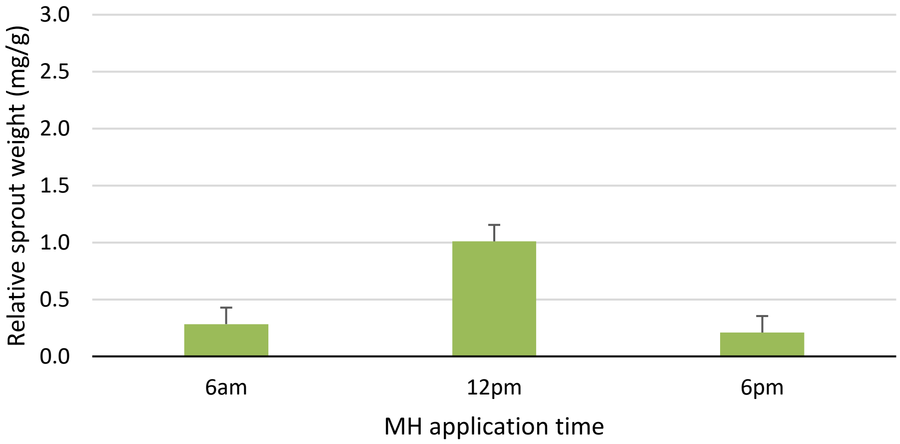
MH levels did not differ with the timing of application at SPot West (ANOVA, $P = 0.892$, Figure 5a) and MH residues in the tubers varied more within the treatments than between the treatments. Mean sprout weight was greater following MH application at 12 pm, than at either 6 am or 6 pm (ANOVA, $P = 0.044$, Figure 5b), indicating that earlier or later applications under more humid conditions may result in more effective control of sprouting, despite the lack of difference observed in MH residues between the treatments (likely partially resulting from small sample sizes).

Figure 5. Effect of MH application during low (12 pm), medium (6 am) and high (6 pm) humidity conditions on *(a)* MH tuber residue (mg/kg) and *(b)* relative weight of sprouts produced (mg sprouts/g tuber) in Russet Burbank at SPot West. Error bars show S.E.

a)



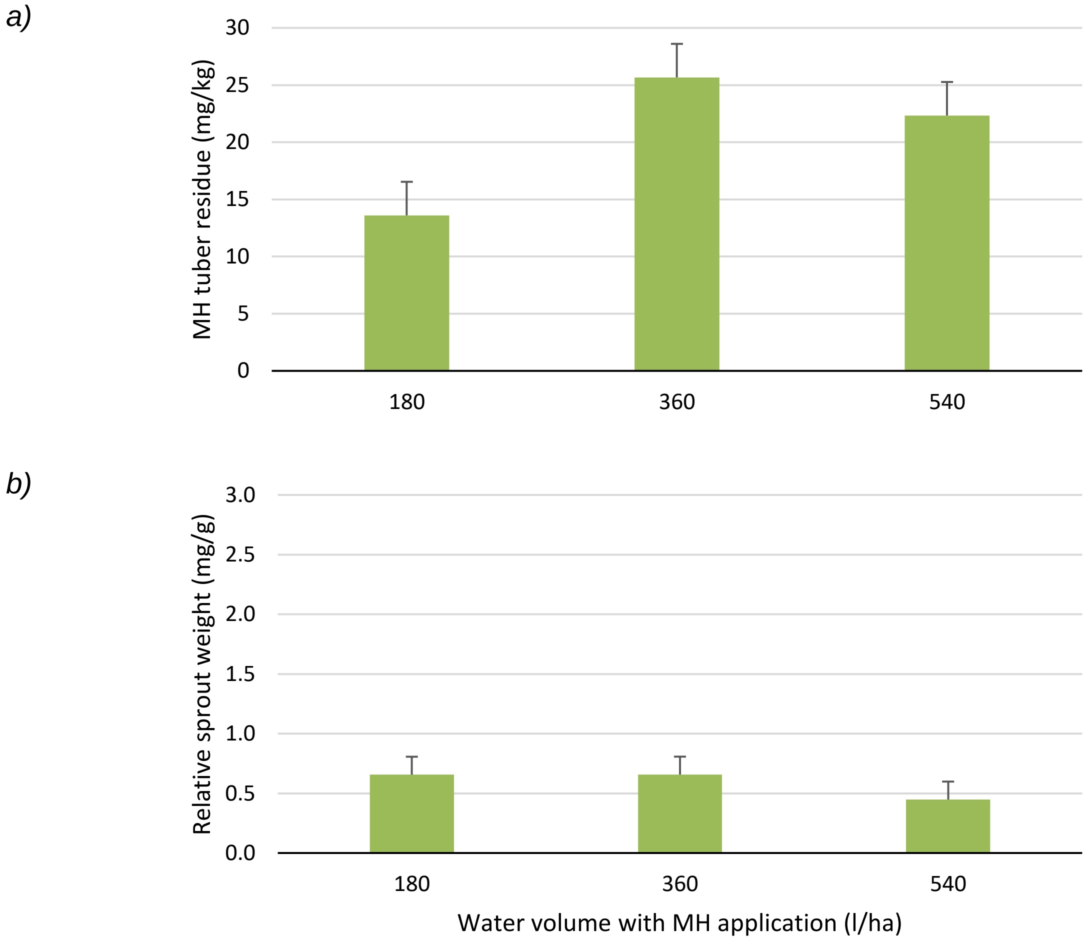
b)



4.1.3. Trial 3

The volume of water used to apply the MH did not affect the MH residue concentrations within the tubers (ANOVA, $P = 0.243$, Figure 6a) or mean sprout weight (ANOVA, $P = 0.809$, Figure 6b). This was due to high variability in both MH residues and relative weight of sprouts within each treatment, though Figure 6 suggests that a higher volume of water could increase tuber uptake of MH.

Figure 6. Effect of MH application with 180, 360 and 540 l/ha of water on *(a)* MH tuber residue (mg/kg) and *(b)* relative weight of sprouts produced (mg sprouts/g tuber) in Russet Burbank at SPot West. Error bars show S.E.

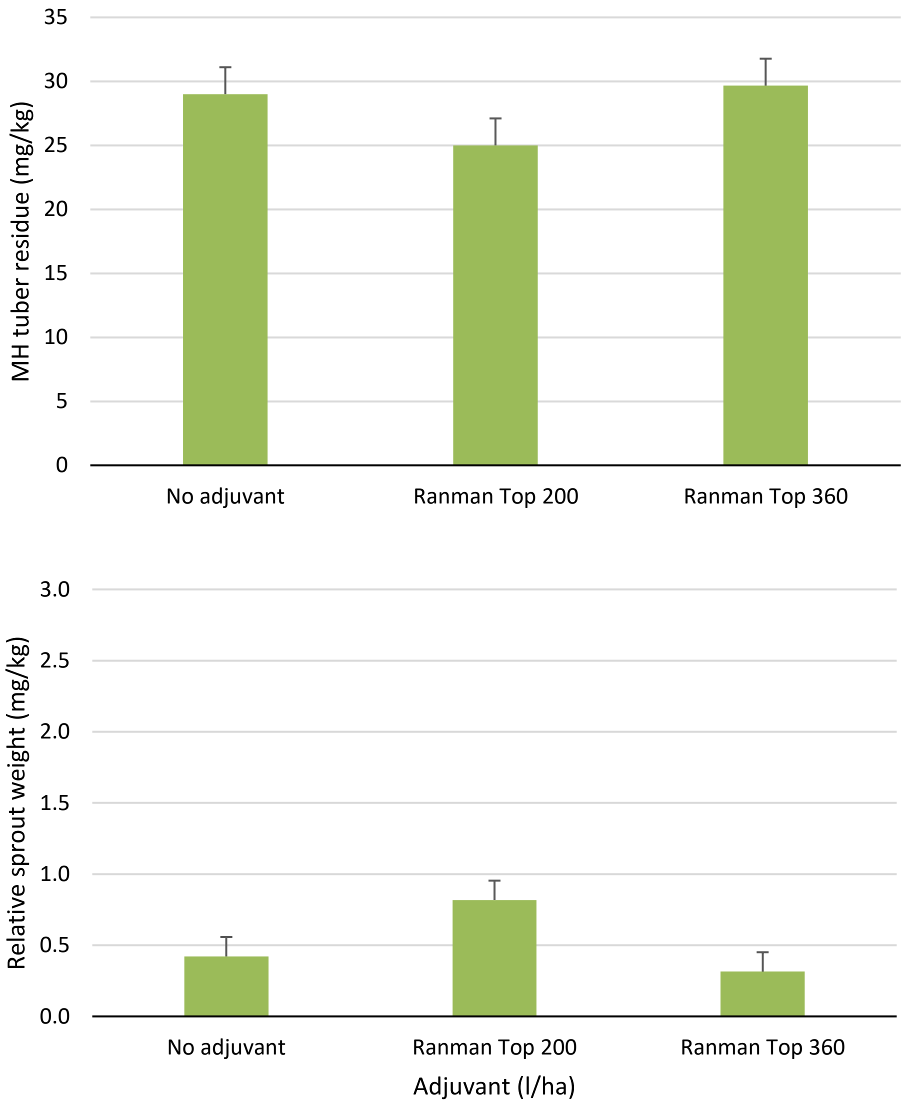


4.1.4. Trial 4

The inclusion of Ranman Top as an adjuvant had no effect upon the MH residue concentrations in the tubers (ANOVA $P = 0.682$, Figure 7a) or on mean sprout weight (ANOVA, $P = 0.282$, Figure 7b), due to high within treatment variability.

Figure 7. Effect of MH application with 200 l/ha Ranman Top, 360 l/ha Ranman Top or without Ranman Top (no adjuvant) on *(a)* MH tuber residue (mg/kg) and *(b)* relative weight of sprouts produced (mg sprouts/g tuber) in Russet Burbank at SPot West. Error bars show S.E.

a) *b)*



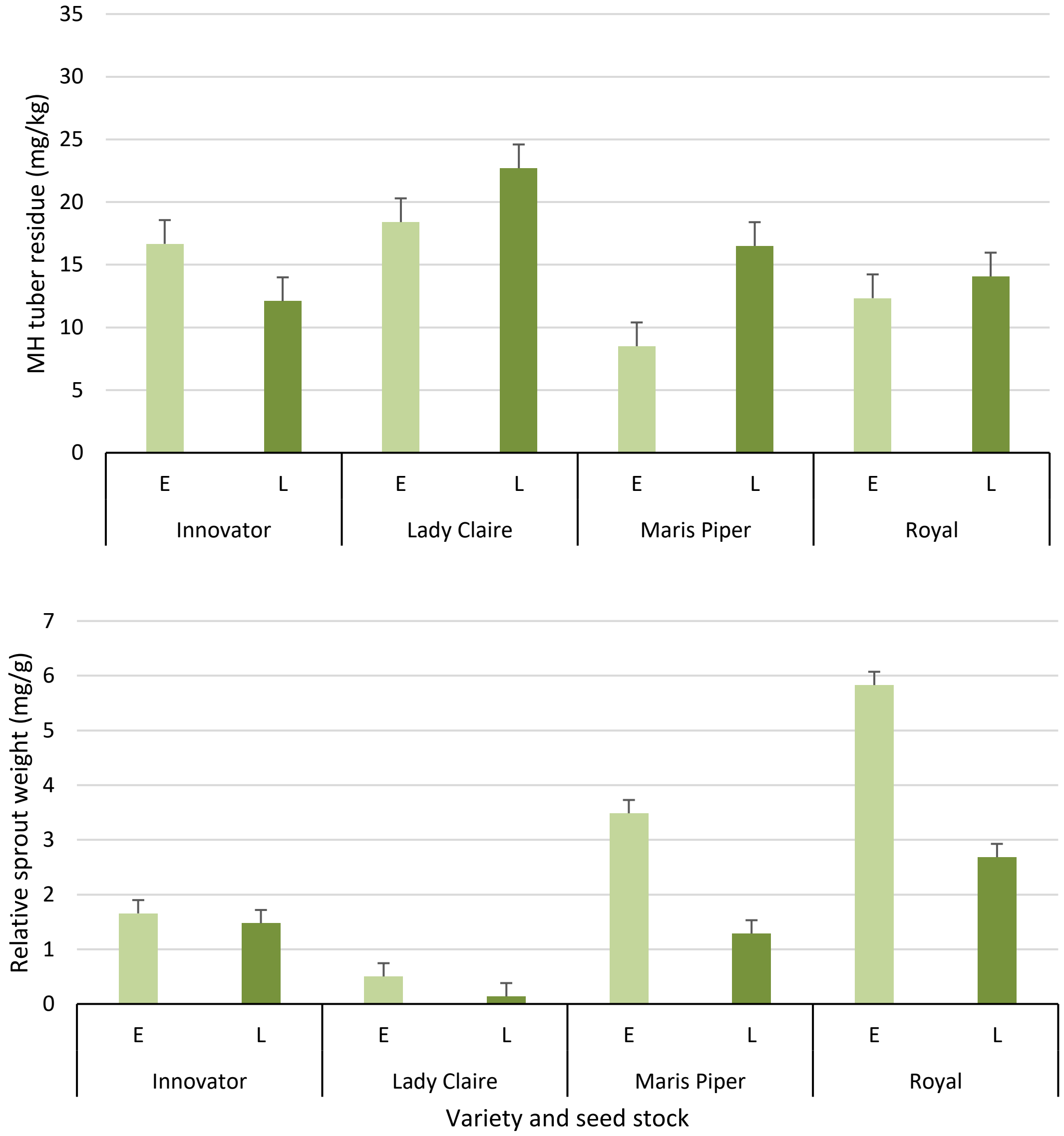
4.1.5. Trial 5

Tuber MH residue concentrations did not differ significantly between varieties in different determinancy groups (ANOVA, $P = 0.455$, Figure 8a) or between stocks within varieties at (ANOVA, $P = 0.619$, Figure 8a). However, sprout production did differ between varieties (ANOVA, $P < 0.001$). Sprout production was greatest in Royal, followed by Maris Piper and Innovator whilst Lady Claire produced the fewest sprouts and on average the early planting produced more sprouts (by weight) than late planting (ANOVA, $P = 0.023$), with the greatest differences in Maris Piper and Royal (Figure 8b). There was an outlier in the late planted Maris Piper, with an MH residue of 130 mg/kg in one sample and it was excluded from analysis since it was not representative of average tuber residues.

Figure 8. **Effect of determinacy level and seed stock on *(a)* MH tuber residue (mg/kg) and *(b)* relative weight of sprouts produced (mg sprouts/g tuber). Varieties were from determinacy groups 1 (Innovator), 2 (Lady Claire), 3 (Maris Piper) and 4 (Royal), with early (E) and late (L) plantings at SPot West. Outlier in late planted Maris Piper not shown (130 mg/kg MH tuber residue, <0.01 mg/g sprout). Error bars show S.E.**

a)

b)



4.2. SPot North

4.2.1. Trial 1

MH tuber residues increased with increasing concentration of MH applied and, when 200 and 300 % of the recommended dose was applied, mean tuber MH residues exceeded the MRL (Figure 9). The MRL was also exceeded in one plant at 125 % and two plants at 150 %. Whilst this was not common, these examples show that it is risky to exceed the recommended application rate due to variable uptake of MH between plants. Weight of sprouts produced did not decrease consistently with increasing MH application rates (ANOVA, P = 0.138, Figure 10).

Figure 9. Mean MH residue concentration in tubers following 100, 125, 150, 200 and 300 % applications of MH in Maris Piper at SPot North. Maximum residue limit shown in red and error bars show S.E.

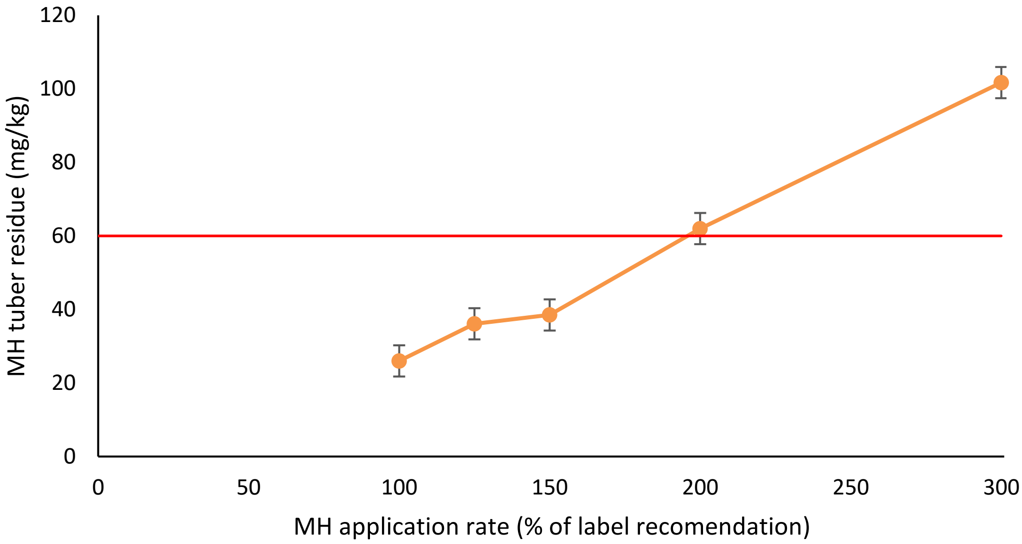
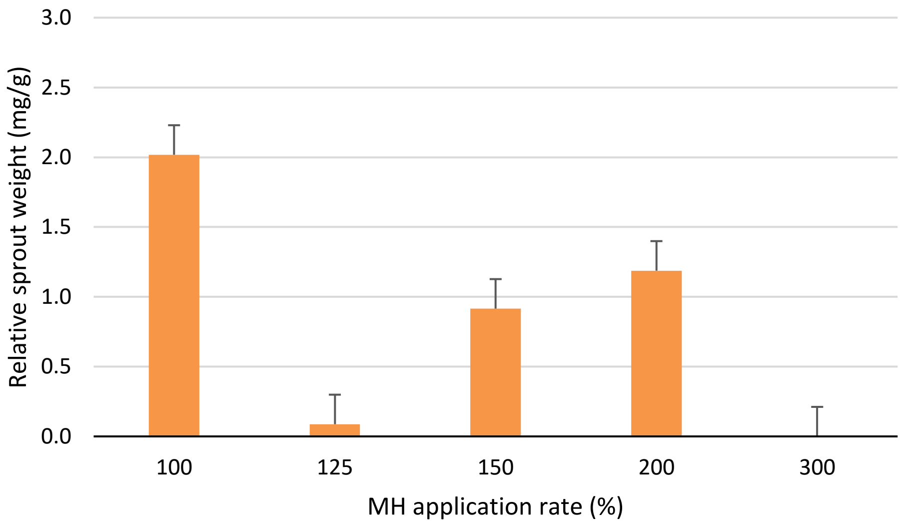


Figure 10. Effect of MH following 100, 125, 150, 200 and 300 % applications of MH on relative weight of sprouts produced (mg sprouts/g tuber) in Maris Piper at SPot North. Error bars show S.E.



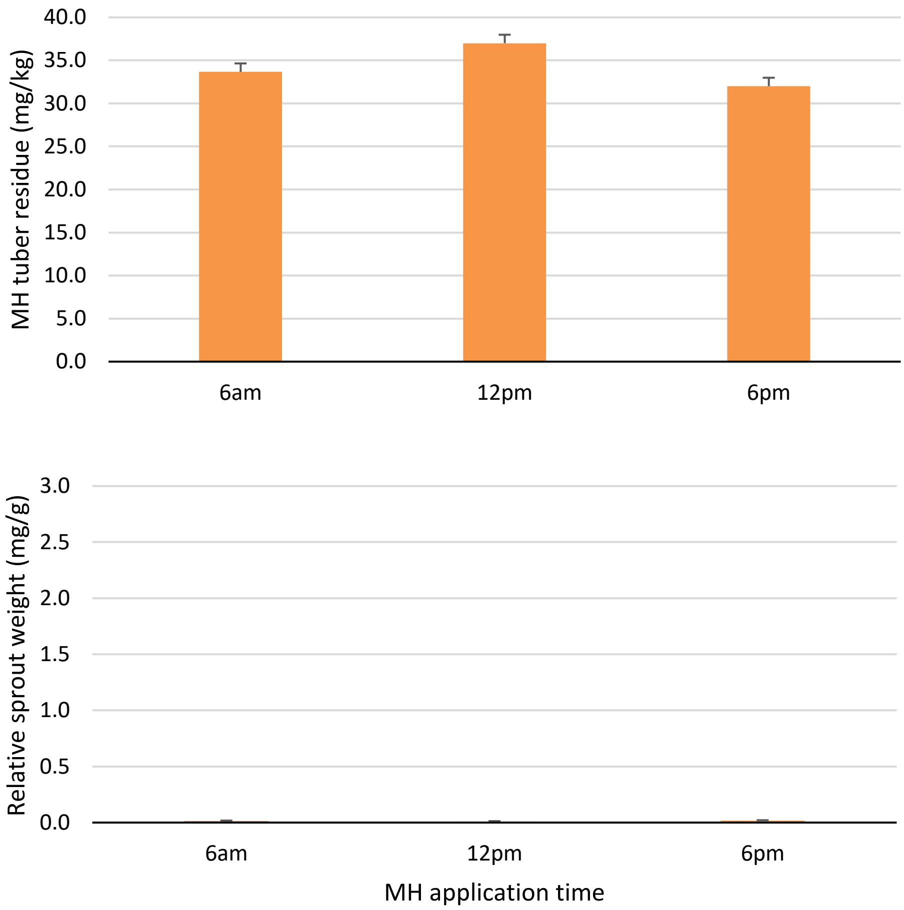
4.2.2. Trial 2

MH levels did not differ with the timing of application (ANOVA, P = 0.086, Figure 11a) and nor did relative sprouting (ANOVA, P = 0.655, Figure 11b). There was very little sprouting in any of the treatments likely due to the additional MH application.

Figure 11. Effect of MH application during low (12 pm), medium (6 am) and high (6 pm) humidity conditions on *(a)* MH tuber residue (mg/kg) and *(b)* relative weight of sprouts produced (mg sprouts/g tuber) in Maris Piper at SPot North. Error bars show S.E.

a)

b)

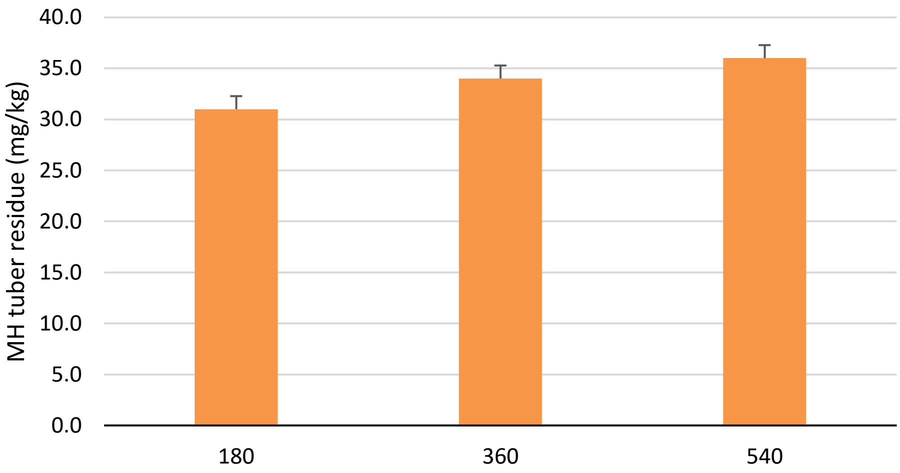


4.2.3. Trial 3

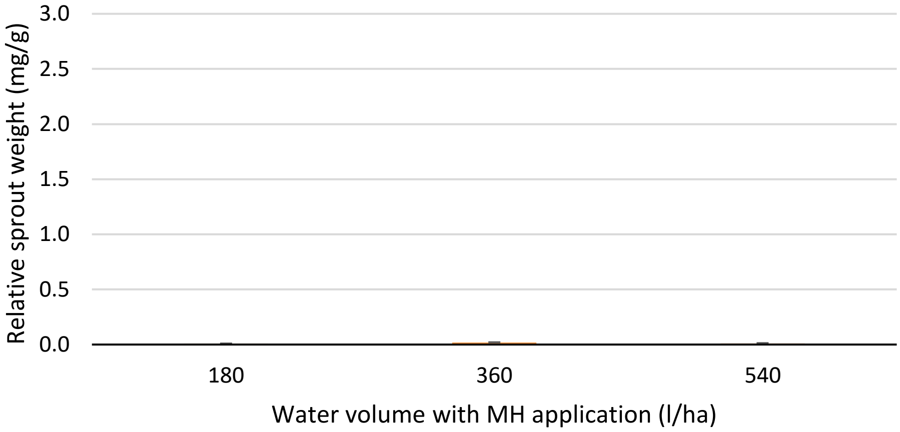
The volume of water used to apply the MH did not affect the MH residue concentrations within the tubers (ANOVA, $P = 0.312$, Figure 12a) or mean sprout weight (ANOVA, $P = 0.349$, Figure 12b). Again, sprouting was minimal, likely due to the additional 100 % application of MH.

Figure 12. Effect of MH application with 180, 360 and 540 l/ha of water on *(a)* MH tuber residue (mg/kg) and *(b)* relative weight of sprouts produced (mg sprouts/g tuber) in Maris Piper at SPot North. Error bars show S.E.

a)



b)

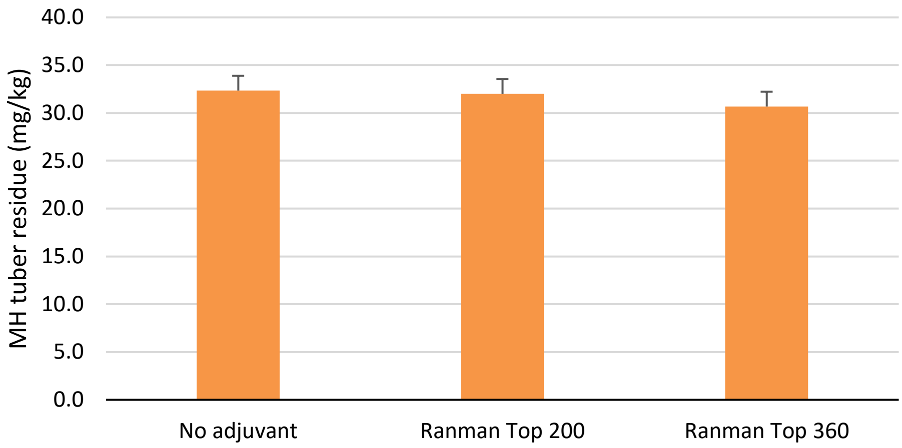


4.2.4. Trial 4

The inclusion of Ranman Top as an adjuvant had no effect upon the MH residue concentrations in the tubers at SPot North (ANOVA, P = 0.922, Figure 13a) or on mean sprout weight (ANOVA, P = 0.823, Figure 13b). Again, the additional MH application applied before the treatments combined with the treatments provided very effective control of sprouting (Figure 13b).

Figure 13. Effect of MH application with 200 l/ha Ranman Top, 360 l/ha Ranman Top or without Ranman Top (no adjuvant) on *(a)* MH tuber residue (mg/kg) and *(b)* relative weight of sprouts produced (mg sprouts/g tuber) in Maris Piper at SPot North. Error bars show S.E.

a)



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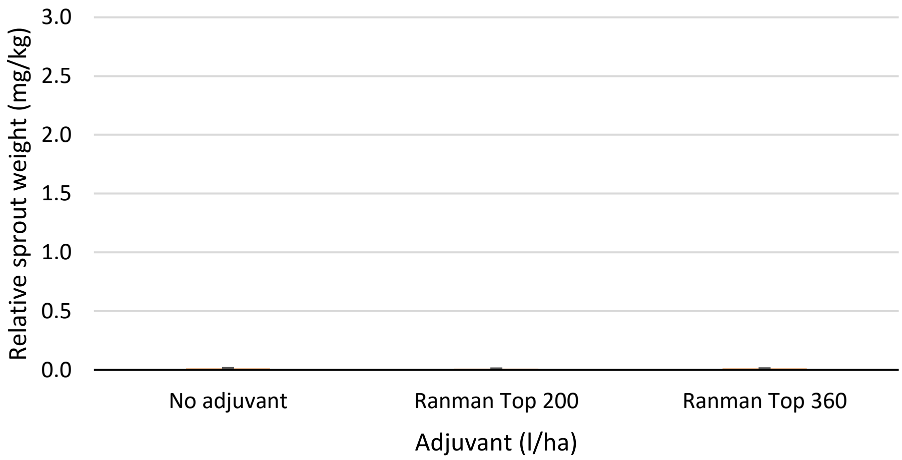
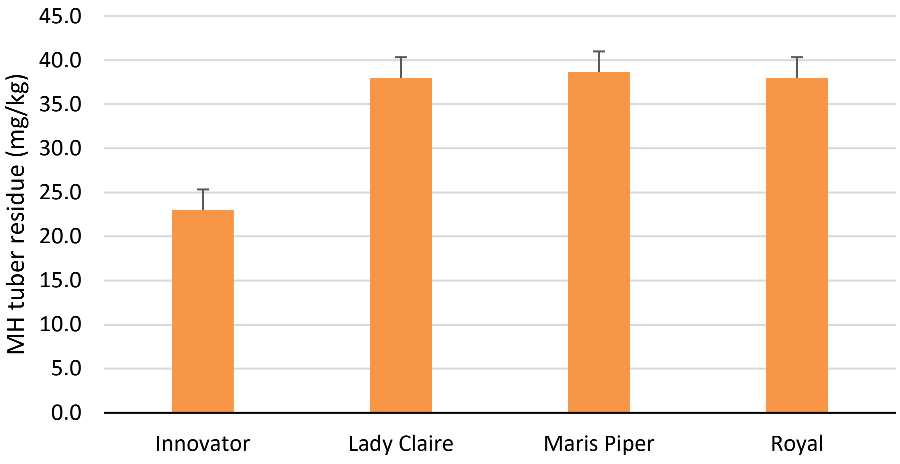


4.2.5. Trial 5

MH tuber residues were lower in Innovator (determinacy group 1) than in the other varieties (ANOVA, $P = 0.013$, Figure 14a) and sprouting was greatest in Innovator although the difference was not significant and sprout weight was low across all varieties (ANOVA, $P = 0.257$, Figure 14b).

Figure 14. Effect of determinacy level and seed stock on *(a)* MH tuber residue (mg/kg) and *(b)* relative weight of sprouts produced (mg sprouts/g tuber). Varieties were from determinacy groups 1 (Innovator), 2 (Lady Claire), 3 (Maris Piper) and 4 (Royal, planted at SPot North. Error bars show S.E.

a)

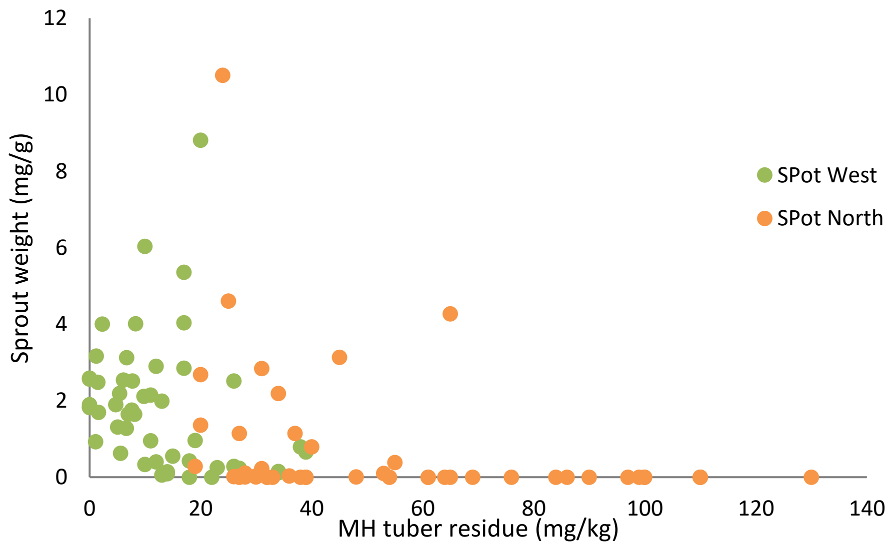


b)

5. Discussion

Overall, MH provided relatively good control of sprouting across both sites, with mean relative sprout weight not exceeding 6 mg/g of tuber and mean MH tuber residue between 15 and 28 mg/kg (SPot West trials 2-5). Across both sites MH residues typically increased with application rates (Figure 15) however this relationship was not linear, reflecting the findings of earlier work (Briddon *et al.* 2020). At the higher rates of MH application there were large differences in MH tuber residues between tubers at SPot North and SPot West; at 200 % total application of MH, tuber residues were 62.0 and 22.4 mg/kg, respectively. Some of these differences in tuber MH residues may be due to the number and timing of the MH applications, and the (unplanned) split application of MH at SPot North may have enabled greater uptake as the first application was applied a week earlier when the canopies were growing more vigorously, with the second application acting as a top-up. The plateauing of the MH uptake at SPot West—above 100 % MH application—suggests that there may be a limit to the amount of MH which can be absorbed by the canopy from a single application, yet MH tuber residues did not plateau at SPot North so it is unclear how split applications may change the effectiveness of MH uptake. Differences between sites may have been due to differences in application conditions or MH uptake between Maris Piper and Russet Burbank and it would be useful to assess this in a replicated trial comparing MH uptake in both varieties in the same location. The rest of the discussion focuses on the SPot West results as the additional 100 % MH application at SPot North greatly reduced the variability of both MH tuber residues and sprout control, masking any variation between the treatments.

Figure 15. Mean MH residue concentration (mg/kg) and weight of sprouts produced (mg/g) in tubers following 0, 25, 50, 100 and 200 % applications of MH at SPot North (orange) and SPot West (green). At SPot North there was an additional 100 % application.



5.1. Between plant variation

Variability in MH uptake is an ongoing challenge for the industry as it moves away from dependence on CIPC for sprout control of stored tubers (Briddon *et al.* 2020), and the range of MH tuber residues has the potential to be problematic at both ends of the spectrum. There was a wide range in MH residues, and the lowest tuber residues uptake were between *c.* 25 and 50 % of the mean value (Appendix 1, and as previously observed by Briddon *et al.* (2020) early dormancy break of some tubers will necessitate application of in-store sprout suppressants (such as ethylene, mint oil or DMN) earlier than required by most tubers. Consequently, good sprouting control of most tubers by MH is not sufficient to avoid early application of in-store sprout suppressants. Similarly, data from SPot North highlighted the risk of over-application of MH in attempt to increase mean tuber residues and provide more comprehensive sprout suppression, as 10-20 % of plants exceeded the MLR at 125 and 150 % rate applications. Improving crop uniformity may help to reduce this between plant variability in MH uptake, as even emergence should result in synchronous canopy development, increasing the likelihood that plants will be at the same stage of canopy maturity and therefore able to absorb more consistent amounts of MH across the crop. Reducing the variability of tuber sizes within a crop will also improve sprouting control since less MH is partitioned to smaller tubers, resulting in greater sprouting (Newberry & Thornton 2007) and Appendix 2. Hence, planting more tightly graded seed should also help to reduce variation in stem and tuber populations, thereby resulting in more even MH residues across the crop and more uniform control of sprouting.

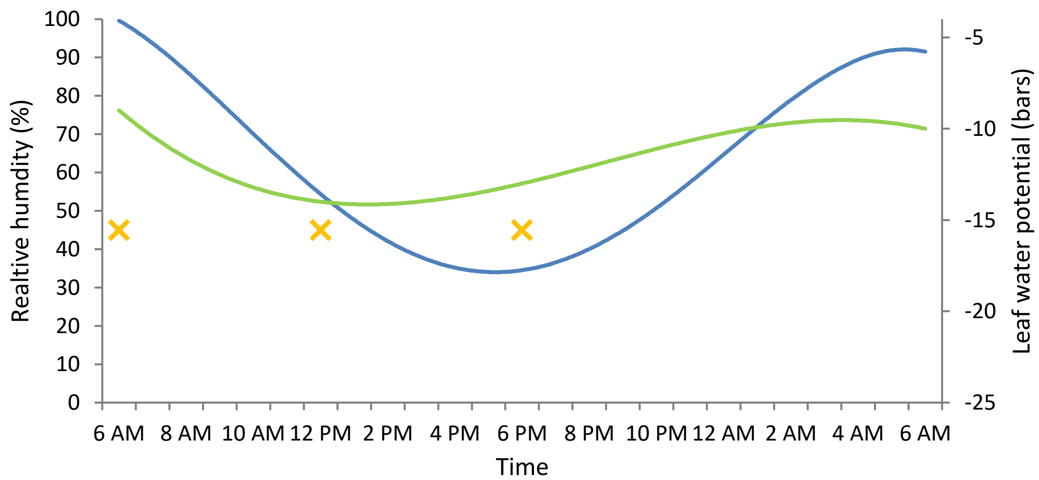
Weight of sprouts decreased with increasing MH tuber concentration, but this relationship was highly variable (Figure 15), more so than in earlier work (Briddon *et al.* 2020). This weak correlation may be explained by the lower overall level of sprouting in the 2021/22 experiments compared to those in 2019/20, as shown by comparison of the weight of sprouts produced by the controls; at 0 % MH application mean weight of sprouts was 13.8 and 21.3 mg/g in Maris Piper and Titan respectively (Briddon *et al.* 2020), but 2.1 mg/g in Russet Burbank (2021/22) and therefore there was limited scope for separation between treatments. This may be due to differences between the experiments in conditions at MH application, seed age or inherent dormancy of the varieties. Previous work has shown that Russet Burbank has higher inherent dormancy than either Titan (Harper 2020) or Maris Piper (Harper 2019; Harper & Head 2021) hence producing fewer sprouts over a similar storage period.

5.2. Application timing

Applying MH either earlier or later during the day resulted in better control of sprouting than MH application at midday. At both SPot North and SPot West, conditions at MH application were relatively cloudy and breezy and results could have been quite different under less humid weather conditions. Differences in MH tuber residues in 2021/22 were smaller than following the humid and dry conditions generated experimentally by Briddon & Winmill (2021)—2.4 mg/kg compared to 20.1 mg/kg—though this is unsurprising as the differences in humidity between the in-field MH applications were more modest in comparison to those generated experimentally.

Both high leaf hydration or turgidity (Smith *et al.* 1959) and high humidity (Smith *et al.* 1959; Briddon & Winmill 2021) have been shown to improve MH uptake, with differences in relative humidity having the greatest influence over MH uptake (Smith *et al.* 1959), but these factors can vary considerably over a 24-hour period in the field as illustrated in Figure 16. Whilst humidity is highest and water stress is lowest at 6 am, these beneficial conditions diminish over the day as the air typically dries and the plant also loses water via evapotranspiration, so conditions become less amenable for MH uptake over the next 12 hours. At a 12 pm application leaf turgidity is likely to be lowest, with the greatest plant stress and relative humidity is also low, resulting in the least optimal MH application conditions. Then at 6 pm, relative humidity is lowest, but will increase over the next 12 hours as temperatures decrease and leaves are also rehydrating under cooling conditions, becoming more turgid, so conditions are improving. The similarity in sprout suppression between the 6 am and 6 pm applications suggests that the benefits of initially well-hydrated leaves and high relative humidity are offset by the subsequent decreases in these factors whilst at 6 pm the reverse occurred and any disadvantage of initially poor conditions is compensated for by increases in relative humidity and leaf turgidity overnight.

Figure 16. Illustration of changes in relative humidity (blue) and potato plant water stress (green) under field conditions over 24 hours. Humidity data from field measurements at Cambridge in June 2021 and leaf water stress—indicated by leaf water potential—measured by Cary and Wright (1971) **in July, in Idaho. Timing of experimental MH applications illustrated with gold crosses.**



These results support the importance of following label advice—only applying MH to unstressed crops—since even small reductions in plant moisture (before the wilt point is passed) can greatly reduce the MH absorbed (Smith *et al.* 1959). Yet absolute differences in sprout suppression between treatments were relatively small and time of application may have a smaller role in optimizing MH uptake than choosing a more overcast and humid day to reduce crop stress at and after MH application.

5.3. Water volume

Applying MH with different volumes of water had no effect on either MH tuber residues or control of sprouting. This suggests that increasing the volume of water applied had no significant benefit upon humidity within the canopy, nor leaf hydration and the ability of the crop to absorb MH.

5.4. Adjuvants

Similarly, including Ranman Top as an adjuvant with MH applications did not result in a significant effect, either positive or negative, on either MH tuber residues or sprouting control. Combining the applications would reduce the number of spray operations so could still be beneficial.

5.5. Variety determinacy

At SPot West, control of sprouting was better in more determinate varieties than more indeterminate varieties despite no significant differences in MH tuber residues. The differences in sprout control between the early and late plantings suggest that differences in MH uptake were due to differences in crop development at the point of MH application not inherent characteristics of each variety. This difference was most apparent in the more indeterminate varieties, Maris Piper and Royal (Figure 8b). Whilst there were no large differences in canopy cover at the point of MH application (personal communication Watts, 2022) the early planted plots were likely closer to the onset of senescence than the late plantings so were likely to be less able to absorb MH when applied on the same date than the late-planted plots of the same variety. Unfortunately, the extent of canopy cover at MH application at SPot West was not recorded in Trial 5, hence it is unknown if this hypothesis was a suitable interpretation of the experiment.

Differences in MH uptake between varieties may also be linked to differences in tuber bulking, since MH is translocated to actively growing tissues (Smith *et al.* 1959; Cunnington 2019) and the rate of tuber bulking can differ significantly between varieties and determinacy groups (Howlader & Hoque 2018; Khan *et al.* 2019). The differences in sprout suppression between planting dates could also be explained by the yield dilution theory (Briddon & Stroud 2021), since earlier planting typically results in a larger yield compared to delayed planting. This effect is more noticeable in more indeterminate varieties which are more sensitive to differences in planting date and season length than determinate varieties (Roberts 2019). If a similar volume of MH was absorbed by the canopies of both the early- and late-plantings then the concentration of MH in individual tubers would be 'diluted' as the MH must be divided between a larger number of tubers. Unfortunately, yield was not recorded at harvest so this second theory could not be tested here either.

The results from SPot West could support either the canopy maturity hypothesis or the yield dilution hypothesis since canopies of the early-planted plots were both likely closer to senescence than the late-plantings (reducing their ability to absorb MH and translocate it to the tubers) and the early-planting also produced a greater yield potentially 'diluting' the concentration MH in individual tubers. Yet the data gathered in this experiment was insufficient to confirm either hypothesis so more work is needed.

Whilst canopy ground cover was complete for all plots at the SPot North MH application, Innovator had a lower MH tuber residue than the more indeterminate varieties. The 25 mg/kg residue in Innovator was similar to residues achieved by a single 100 % application, suggesting that the Innovator plots were at the optimum stage to absorb MH at the earlier application, but—when closer to the point of senescence a week later (Appendix 3, Figure 18)—absorbed little MH at the second application, unlike the other varieties with longer lived canopies. This data suggests that one week can have a large effect upon the effectiveness of MH uptake of determinate varieties. It is acknowledged that it is more difficult to find the right window for MH application, particularly with more determinate varieties—since their canopies are more short-lived and liable to senesce more rapidly than indeterminate varieties (Certis 2020)—hence it is not surprising that MH uptake and sprouting control differed between varieties.

Tuber endodormancy—the period during which tubers will not sprout, even under favourable environmental conditions—also varies between varieties (Harper 2020) and may affect the efficacy of MH applications, independent of MH tuber residues. Varieties with short dormancy periods may produce a greater weight of sprouts at the same MH tuber residue as a variety with a longer period of dormancy. Royal has a short to medium period of endodormancy (Harper 2019, 2020; Harper & Head 2021) which may explain its greater sprout production at SPot West relative to the other varieties. However, in the same study Lady Claire demonstrated a dormancy period 20 days shorter than that of Royal (Harper & Head 2021), yet did not produce a correspondingly high number of sprouts at SPot West—in these experiments sprout production was lowest in Lady Claire (<1 mg/g of sprouts, Figure 8b). Hence data on varietal dormancy may help explain some of the variation in efficacy of sprout suppression, though it will not explain it all.

Despite variation between varieties, at both sites mean MH residues were greater than 12 mg/kg (apart from early-planted Maris Piper at SPot West; 8.5 mg/kg), which has been suggested as the minimum residue required for adequate control of sprouting (Cunnington 2019). Reasonable sprout control was achieved across the four varieties, though the results show the need to monitor sprouting on a varietal basis and storing varieties with differing degrees of dormancy separately will allow more appropriately targeted applications of in-store sprout suppressants. Additionally, understanding that variety determinacy will influence MH uptake and the timing of application will equip growers to plan MH applications appropriately.

6. CONCLUSIONS

Over 22 weeks of storage, the recommended label dose of MH (5 kg Fazor in 360 l water, with 600 g/kg maleic hydrazide) provided moderately effective sprout suppression without application of further sprout suppressants in store and the maximum length of sprouts produced by Russet Burbank was <15 mm across trials 1-4 (Appendix 4).

MH levels were variable both within- and between-plants at both high and low MH application rates which will continue to pose a problem for store managers who must decide which tubers sprouting will drive their application of in-store sprout suppressants. Since smaller tubers have lower residues of MH, tuber residue uniformity could be improved by grading out small tubers and either disposing of them if they do not meet market requirements, or storing them separately, to enable more targeted application of in-store sprout suppressants to just those which need it.

This variability, in combination with a small number of replicates, meant that few significant differences were report in MH tuber residues across the trials, even though there were differences in sprout suppression in some cases. More uniform crops will likely result in more consistent MH uptake and less between-tuber variation in MH residues but this hypothesis needs confirming by further experiments.

Split applications of MH may be a more effective way to increase tuber uptake, though 100 % total rate of application should not be exceeded due to the risk of exceeding the MRL. Controlled experiments comparing MH uptake and sprout suppression are required to identify the optimum split dosage, if any.

Midday MH applications should be avoided as sprout suppression was more effective following either early morning or evening applications. MH uptake was greater earlier in the day likely due to low levels of crop stress and uptake is likely to be greater in the evening where more humid conditions overnight promoted MH uptake by keeping it in solution on the leaves for longer. The relative importance of high leaf turgidity and high humidity following MH application will likely depend on the temperature and humidity conditions of a given day. Growers would continue to be advised to select days for MH application which are cooler with high humidity forecast and to make sure that the crop is unstressed—either by dehydration, pests or disease, as per the product label. Since conditions are typically more variable between days than within a day selecting the optimal day is expected to be more important than varying application time within the day.

Whilst larger volumes of water in an MH application were thought to improve MH uptake by keeping MH in solution on the leaves for longer there was no significant effect of varying the volume of water in these trials. However, the results from SPot West did suggest that MH uptake was lower at 180 l/ha of water. Increasing water volume may improve MH uptake under drier, less favourable conditions but these are best avoided in the first instance and further experiments would be required to test this. Similarly, including Ranman Top as an adjuvant when applying MH had no effect on MH tuber residues or sprout control despite expectations that it would reduce MH uptake. If both Ranman Top and MH are applied in a single pass—reducing fuel, water and labor requirements—the results from SPot West suggest that at least 360 l/ha of water should be applied, rather than the lower volume of water recommended by the Ranman Top label.

Finally, differences in both MH tuber residues and sprout suppression between varieties appear to be a combination of differences in MH uptake, size of yield and dormancy. Determinacy group indicates the likely length of canopy cover for a given variety, from which the 3-5 week window before onset of senescence can be estimated, and MH appropriately applied. Other factors which affect canopy duration, such as seed age, should also be considered when estimating the timing of senescence and planning MH applications. The pattern of tuber bulking also differs between varieties and this likely effects the ability of the plants to transport MH to the tubers. It may also be more difficult to achieve good sprout suppression in crops with larger yields due to 'dilution' of a fixed maximum MH application between a greater number of larger tubers. More work is required to investigate if the 3-5 week pre-senescence window should be adjusted depending on determinacy or varietal differences in tuber bulking.

In summary, growers should continue to follow label advice, monitoring tuber size starting six weeks prior to planned haulm destruction and then applying MH to unstressed crops. High relative humidity following application can also improve uptake. MH application should be managed with regard to variety, especially canopy maturity at application.

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8. APPENDICES

8.1. Appendix 1

Mean MH residues in Maris Piper at SPot North and Russet Burbank at SPot West, in Trial 1. Other summary variables show the variability.

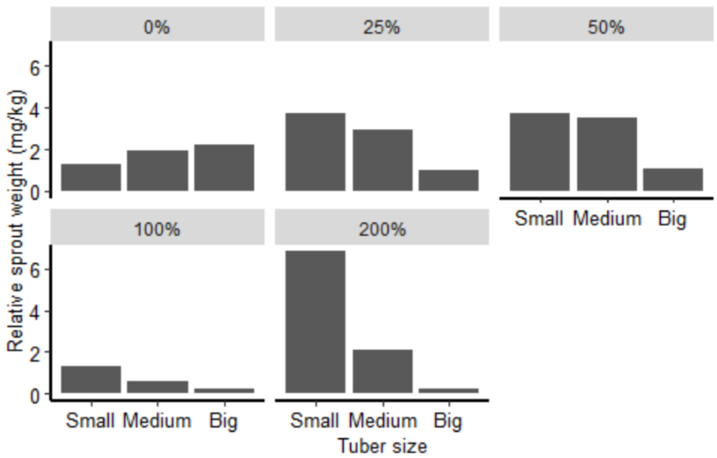
Table 3. Summary statistics for tuber MH residue concentration (mg/kg) following MH application at 0, 25, 50, 100 and 200 % of the label rate. At SPot North, the MH treatments were applied in addition to an accidental additional 100 % dose of MH.

Site	MH rate applied	Mean	Standard deviation	Minimum	Maximum	% difference between minimum and mean
SPot North	100 %	26.0	4.2	19.0	31.0	26.9
	125 %	36.1	12.2	27.0	69.0	25.2
	150 %	38.5	14.3	20.0	65.0	48.1
	200 %	62.0	15.8	45.0	99.0	27.4
	300 %	101.7	13.9	84.0	130.0	17.4
SPot West	0 %	1.0	1.5	0.0	4.7	100.0
	25 %	9.3	4.8	2.3	17.0	24.7
	50 %	10.7	4.6	5.1	18.0	47.7
	100 %	19.3	10.0	6.6	34.0	34.2
	200 %	22.4	10.2	7.6	39.0	33.9

8.2. Appendix 2

Following MH treatment, relative weight of sprouts produced was typically greater in small tubers than larger ones.

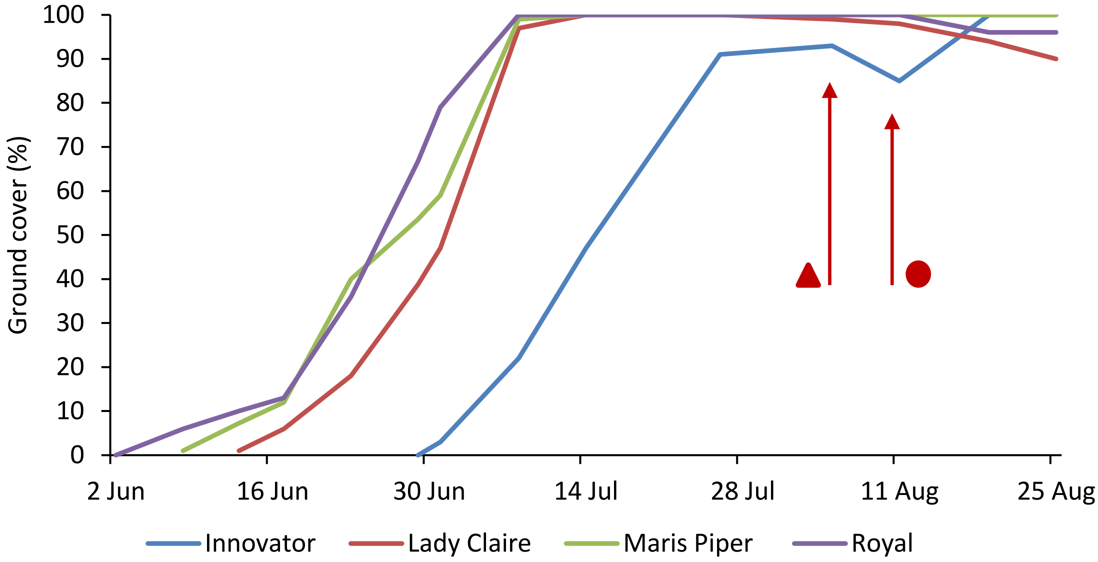
Figure 17. Mean relative weight of sprouts from Trial 1, SPot West (*cv.* Russet Burbank), from small (≤ 60 g), medium (60 > x ≥ 120 g) and large (> 120 g) tubers following application of MH from 0-200 % of the recommended label application.



8.3. Appendix 3

Canopy cover was >95 % at both the experimental and unintentional MH applications for Lady Claire, Maris Piper and Royal. Whereas Innovator canopy cover was much lower (85 % GC) at the experimental MH application, likely resulting in a lower uptake of MH at the later application.

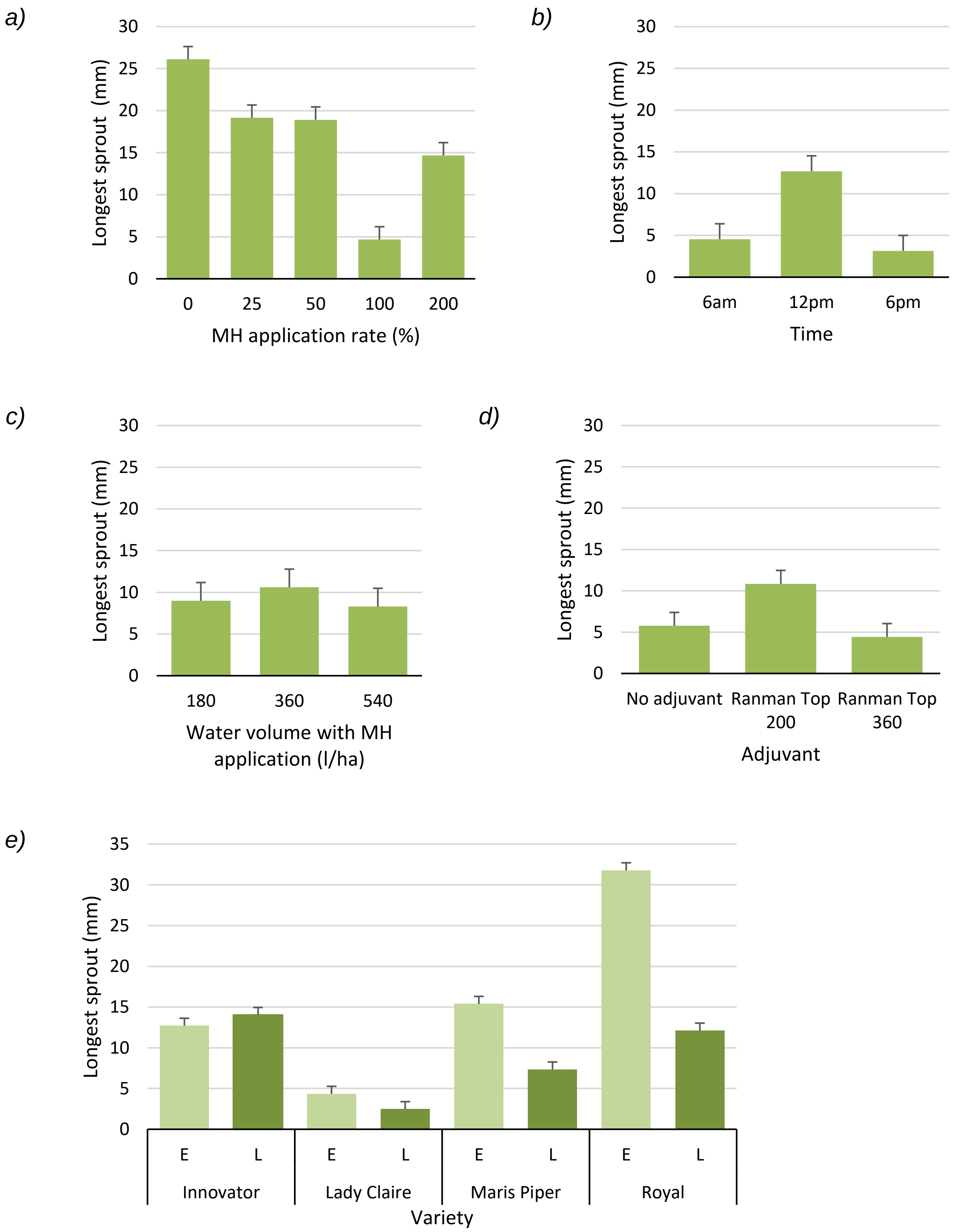
Figure 18. Percentage canopy ground cover of Innovator (blue), Lady Claire (red), Maris Piper (green) and Royal (purple) at SPot North. The dates of the experimental (11 August; ●) and unintentional (5 August; ▲) applications of MH are marked with red arrows. Data courtesy of Crop4Sight.



8.4. Appendix 4

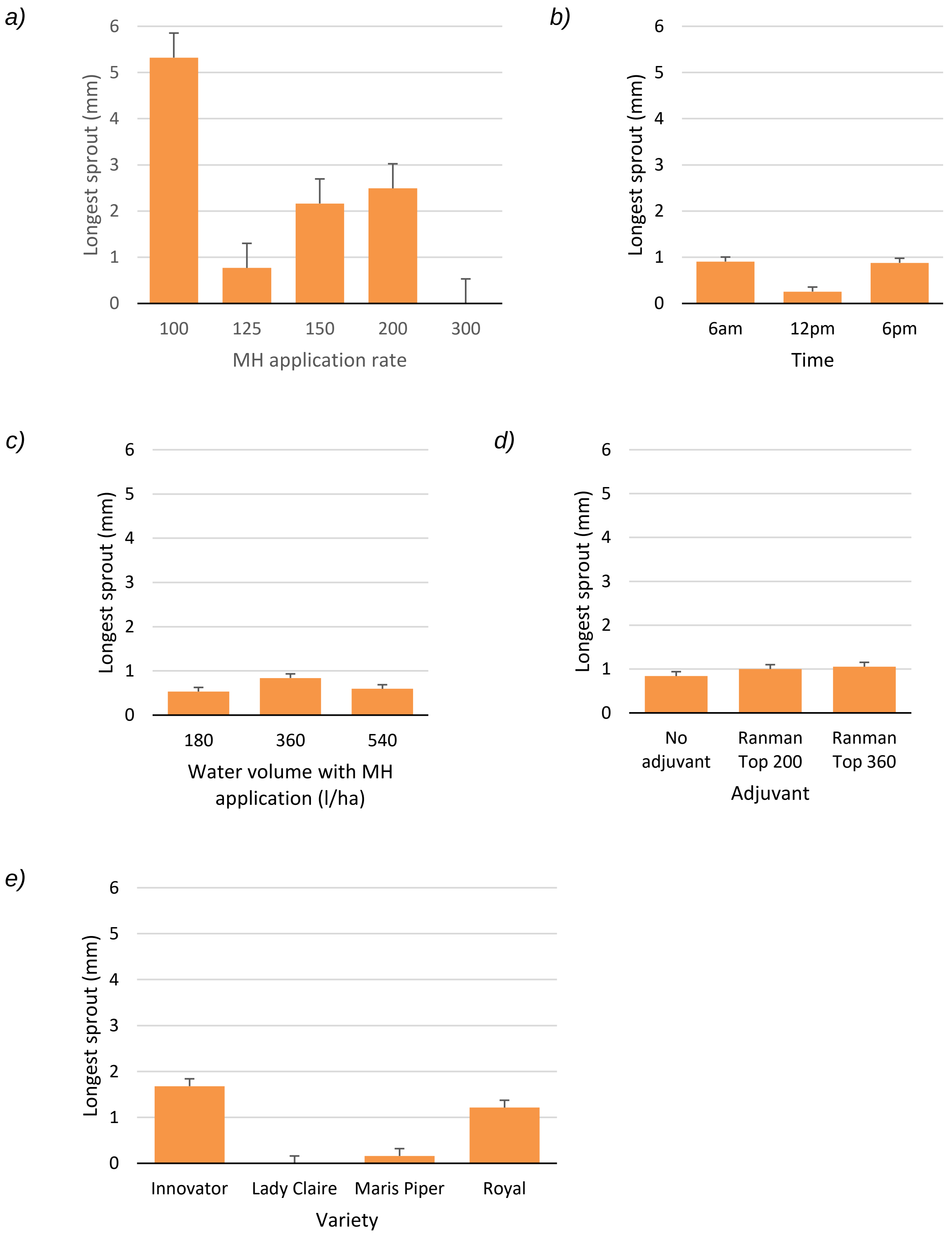
When plots were treated with a full dose of MH at SPot West control of sprouting was fair and the longest sprouts were less than 15 mm, apart from early-planted Maris Piper (15.4 mm) and Royal (31.8 mm).

Figure 19. Mean length of longest sprout produced under each treatment in *a)* Trial 1, *b)* Trial 2, *c)* Trial 3, *d)* Trial 4, and *e)* Trial 5 at SPot West. Experimental treatments are described in the methods.



When plots were treated with a double dose of MH at SPot North control of sprouting was very good and the longest sprouts were less than 3 mm with little variation between treatments.

Figure 20. Mean length of longest sprout produced under each treatment in *a)* Trial 1, *b)* Trial 2, *c)* Trial 3, *d)* Trial 4, and *e)* Trial 5 at SPot North. Experimental treatments are described in the methods.



9. KNOWLEDGE EXCHANGE ACTIVITIES

8 July 2021, SPot North Open Day, Eastoft, Lincolnshire

28 July 2021, SPot West Open Day, Leominister, Herefordshire

14 June 2022, CUPGRA Members' Day, Cambridgeshire

4 August 2022, field walk at Monkhall Farm, Herefordshire

11 August 2022, field walk at RJ & AE Godfrey Farm, SPot North, Lincolnshire

10. ACKNOWLEDGEMENTS

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