Variation in Tuber Size: Multiple Scales, Myriad Causes

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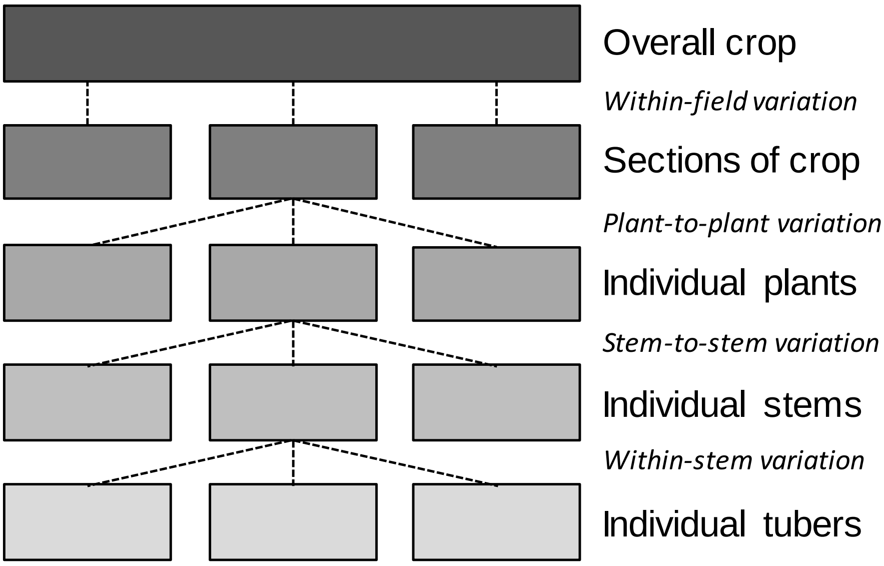
Variation in tuber size within crops can affect marketable yield by increasing the proportion of under- and over-size tubers. Different mathematical models have been used to describe tuber size or tuber weight including Weibull distributions (Bussan *et al*. 2007), gamma distributions (Marshall 2000) and normal distributions (Travis 1987). These methods are preferable to analysing the yield within individual size grades as fewer spurious significant effects occur and more subtle differences in tuber size can be detected (Hall & Glasbey 1993). The method of Travis (1987), who described the tuber size distribution with a normal curve, describes the tuber size distribution with two parameters; mean tuber size where 50 % of yield consists of smaller tubers and 50 % consists of larger tubers, and standard deviation where 68 % of yield is within one standard deviation of the mean tuber size. The standard deviation increases as yield and mean tuber size increase, but the ratio between the standard deviation and the mean tuber size remains stable. This ratio is the coefficient of variation (COV) and is a measure of uniformity. Typical values of the COV of tuber size range from *c.* 12-20 %, which for a typical UK crop at the optimum mean tuber size equates to marketable yields of *c.* 98-84 %. Although tuber weight distributions are not normally distributed, cubic transformations can be used to convert between size and weight, and in turn predict the percentage of yield in any weight grade.

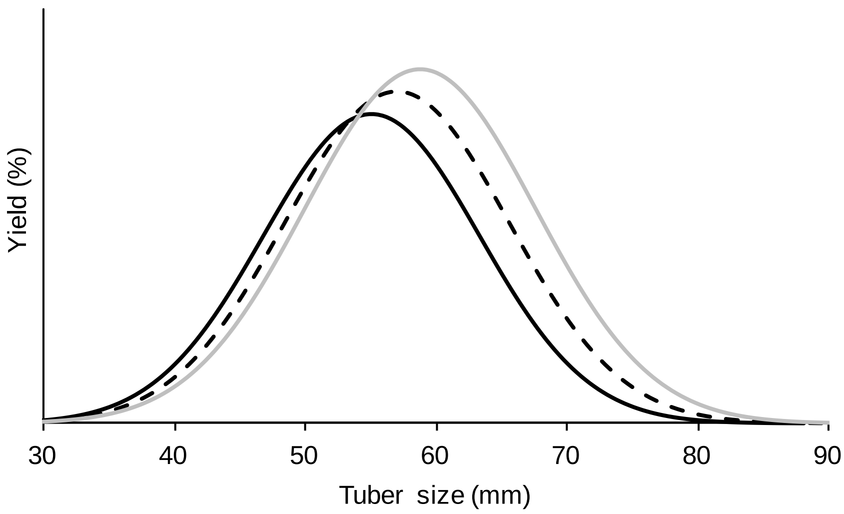
Achieving the target mean tuber size is critical to having a large proportion of the yield within the required grades and is determined by yield and number of tubers. The processes governing each of these are well understood (Allen & Scott 1980; Firman & Daniels 2011) and mean tuber size can therefore be manipulated by varying seed size and spacing (Allen & Wurr 1992). During the season, with knowledge of yield formation, mean tuber size can be predicted in order determine when the optimum economic yield will be achieved, depending on the value of different grades (Stalham 2017). However, variation in tuber size is more difficult to predict and manipulate, with many factors potentially affecting the extent of variation. Variation in tuber size occurs at different levels within a crop (Figure 1) and understanding the mechanisms determining this variation will aid in producing more uniform crops. Analogous to the processes determining mean tuber size, variations in tuber size are caused by variations in yield and the number of tubers.

Figure 1. Different scales at which variation in tuber size occurs within a crop.



At the largest scale, variations in the yield and or number of tubers at different locations within a crop can result in the mean tuber size varying. Factors that affect the yield and number of tubers between crops (e.g. soil type, nutrition, irrigation, pathology) will also affect variation within a crop. The effect on uniformity will depend on the extent of the variation in mean tuber size and currently, there is little quantitative information available on how this varies within crops. Models indicate that some variation in the mean tuber size can be tolerated with only a small effect on uniformity (Figure 2) but more data are required to establish how realistic this is. Technological innovations such as unmanned aerial vehicles and yield mapping may allow us to characterise within-field variations more precisely but these variations would need to be predictable and consistent in order to be managed.

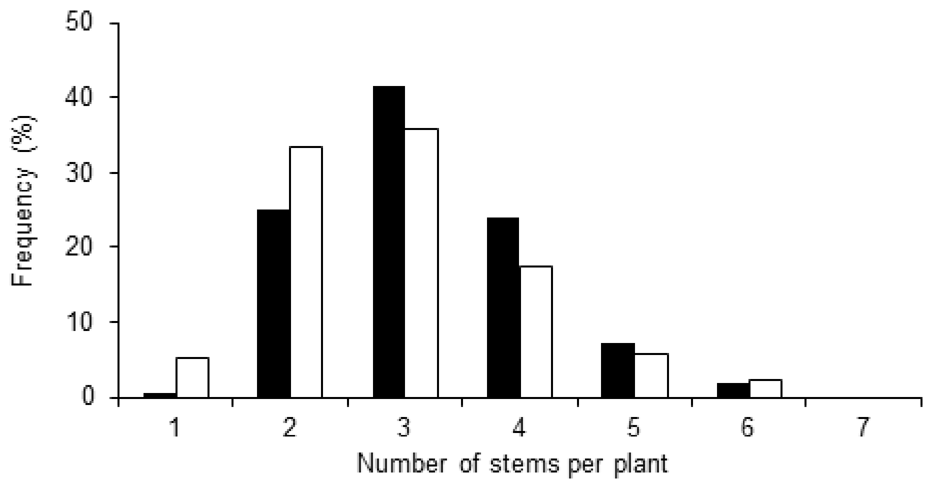
Figure 2. Modelled tuber size distributions for a typical crop with a yield of 60 t/ha, 500k tubers/ha and a COV of tuber size of 15.0 % (- - - -). Areas producing a 10 % lower yield (———) or a 10 % higher yield (———) produce smaller and larger tubers respectively, but the overall COV of tuber size of the entire crop is only moderately increased to 15.4 %.



Plant-to-plant variation has long been noted to occur within potato crops (Stewart 1921; Svensson 1966), but the causes of this variation have been uncertain and whether it has any effect on uniformity has not previously been investigated. Surveys of commercial crops found that plants with a higher yield per stem produced larger tubers, consistent with how for a given yield, the stem density determines the mean tuber size of crops. Several experiments were conducted to establish how variation in seed tuber weight, emergence and within-row spacing affected variation in the yield, number of stems and number of tubers per plant and how these variations affected the overall variation in tuber size. Theoretically, the most uniform crop would consist of evenly spaced, single-stemmed plants that emerged evenly. In reality, crops are far from this ideal, but there would be advantages in manipulating crops to be closer to this situation.

Considering that the mean seed tuber weight affects the number of stems per plant (Firman & Daniels 2011; Allen & Wurr 1992), variation in seed tuber weight was expected to affect variation in the number of stems per plant, which has previously been shown to influence the mean tuber size of plants (Firman and Shearman 2006). Reducing variation in the number of stems per plant would reduce variation in mean tuber size per plant and improve uniformity. However, it was found that reducing variation in seed tuber weight had no significant effect on the variation in the number of stems per plant (Figure 3) and did not affect uniformity. Although the experiments were conducted with Maris Piper, similar relationships between the weight of individual seed tubers and the number of stems per plant were found in other varieties. There are clearly other factors besides seed tuber weight which determine the number of stems per plant and establishing these merits further attention.

Figure 3. The number of stems per plant for crops grown from tightly graded seed (35-45 g) and widely graded seed (25-45 mm, 12-82 g) with the same average weight. Tightly graded seed, ■; widely graded seed, □.



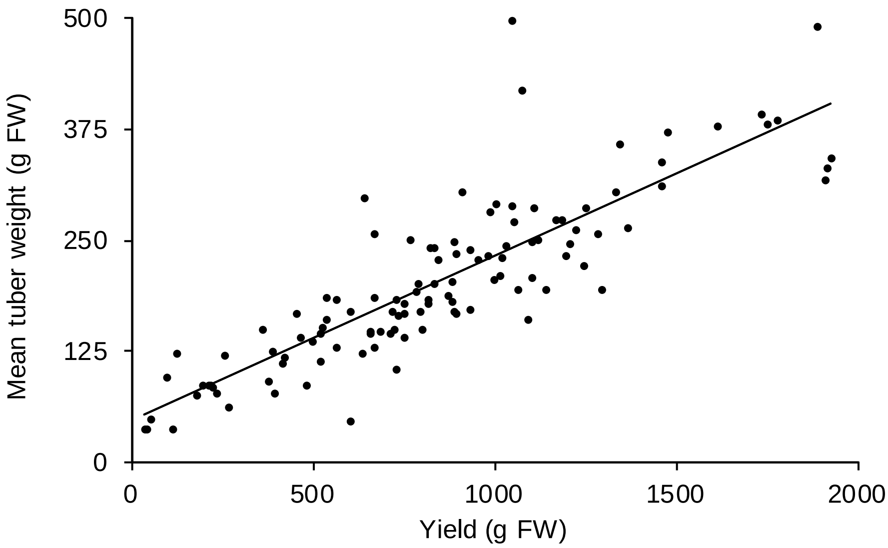
Variation in emergence is known to be important in influencing the uniformity of root vegetable crops, with earlier emerging plants out-competing later-emerging plants and producing larger roots (Benjamin 1990). While emergence is routinely recorded in experiments, it is uncertain whether variation in emergence contributes to causing variation in tuber size. Seed tubers were sprouted prior to planting and split into two groups, one containing evenly sprouted tubers

(2-4 mm long) and the other containing tubers with long and short sprouts (< 2 mm and > 4 mm long). The evenly sprouted seed tubers emerged more uniformly and decreased variation in yield per plant, but did not significantly affect uniformity. However, the differences in emergence between treatments were relatively small in comparison to those that occur between stocks of the same variety grown in different years. Had emergence been more protracted, the results may have differed. Information on the typical duration of emergence in commercial crops is required to establish how substantial any decreases in uniformity that it causes are.

Variation in within-row spacing results in plants growing at different densities which would be expected to cause plants with more space to produce larger tubers than those with less space. While previous experiments (Pavek & Thornton 2006) have found irregular planting can decrease marketable yields, they did not distinguish between whether this was due to differences in the mean tuber size or variation in tuber size. Other experiments have found no influence of variation in within-row spacing on the tuber size distribution (Jarvis *et al.* 1976; Entz & LaCroix 1984; Booth & Allen 1989, 1990). It is necessary to establish what extent of variation in within-row spacing can be tolerated without increasing variation in tuber size. In 2013, seven treatments were examined with levels of variation in within-row spacing ranging from completely uniform to four seed tubers planted within 40 cm of each other, followed by an 80 cm gap. Increasing variation in within-row spacing did not affect overall yield, variation in yield per plant or variation in tuber size. This demonstrated that the growth of the canopy was plastic and compensated for differences in space per plant, so that large differences in space per plant had minor effects on yield per plant. In 2014, the most extreme treatment from the 2013 experiment was compared with uniform spacing in an experiment in Maris Piper and in a separate experiment in Marfona and Markies. In Maris Piper, the COV of tuber size increased by *c.* 1 % by the higher variation in within-row spacing, resulting in a *c.* 2 % decrease in the yield of marketable tubers. The treatment had a much larger effect in Marfona and Markies, increasing the COV of tuber size by *c.* 3 % resulting in a 5 % decrease in the yield of marketable tubers. Yield was decreased by variable spacing in both experiments by *c.* 5 t/ha but the differences could not be explained by differences in ground cover and may have been caused by neighbouring rows compensating and producing a higher yield. Further work is required to establish the varietal traits responsible for the different responses to variation in within-row spacing.

In addition to the experiments, surveys were conducted to examine how seed tuber weight, number of stems per plant and date of emergence affected stem-to-stem variation. As the true unit of population within the potato crop (Allen & Wurr 1992), it is crucial to understand the growth of stems in order to understand the variation that occurs within crops, but no descriptions of stem-to-stem variation exist. It was consistently found that the yield of individual stems was more variable than that of individual plants, and that as the yield of stems increased, they were more likely to produce larger tubers (Figure 4). Within crops, higher yielding stems produced more tubers, but the increase in the number of tubers was not proportional to the increase in yield and therefore was not sufficient to counter the effect of yield per stem on mean tuber weight per stem. Although there was considerable variation in the size of tubers on each stem (the causes of which are uncertain), the consequence of the relationships between yield per stem and mean tuber weight, was that reducing variation in the yield of stems would result in a more uniform crop.

Figure 4. Relationship between the yield of individual stems and the mean tuber weight per stem in Russet Burbank. Mean tuber weight was derived in an analogous way to the mean tuber size of crops, accounting for the distribution of yield between different tubers.



Variation in tuber size is a complex trait with numerous physiological and agronomic causes. This work has made progress towards understanding the underlying causes but there remain many uncertainties, in particular at the level of individual stems. Future work will continue to characterise stem-to-stem variation and will begin to examine variation in tuber size on individual stems, which is a further component of variability that was not explored in the current study.

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