

Brassicas_2021_summarized_results

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This markdown document summarizes the principal results of the Brassica project generation 2 analyses. Analyses are not performed within this document; prior to running this file, the results should be generated by running the two other .Rmd files in this repository: “Brassicas_2021_morphology.Rmd” and “Brassicas_2021_rnaseq.Rmd”.

Work package 1: Comparing domesticates to their wild progenitors

For this work package, we wish to compare wild progenitor species to modern domesticates. For Brassica, the comparison is between domesticated *B. rapa* with wild *B. rapa*, while for Raphanus the comparison is between *R. raphanistrum* (wild) and all other *Raphanus* samples, all of which appear to be domesticated.

Brassica gene expression

For the gene expression analysis, our model design is:

$$\text{geneexpression} \sim \text{domestication} + \text{treatment} + \text{domestication} * \text{treatment}$$

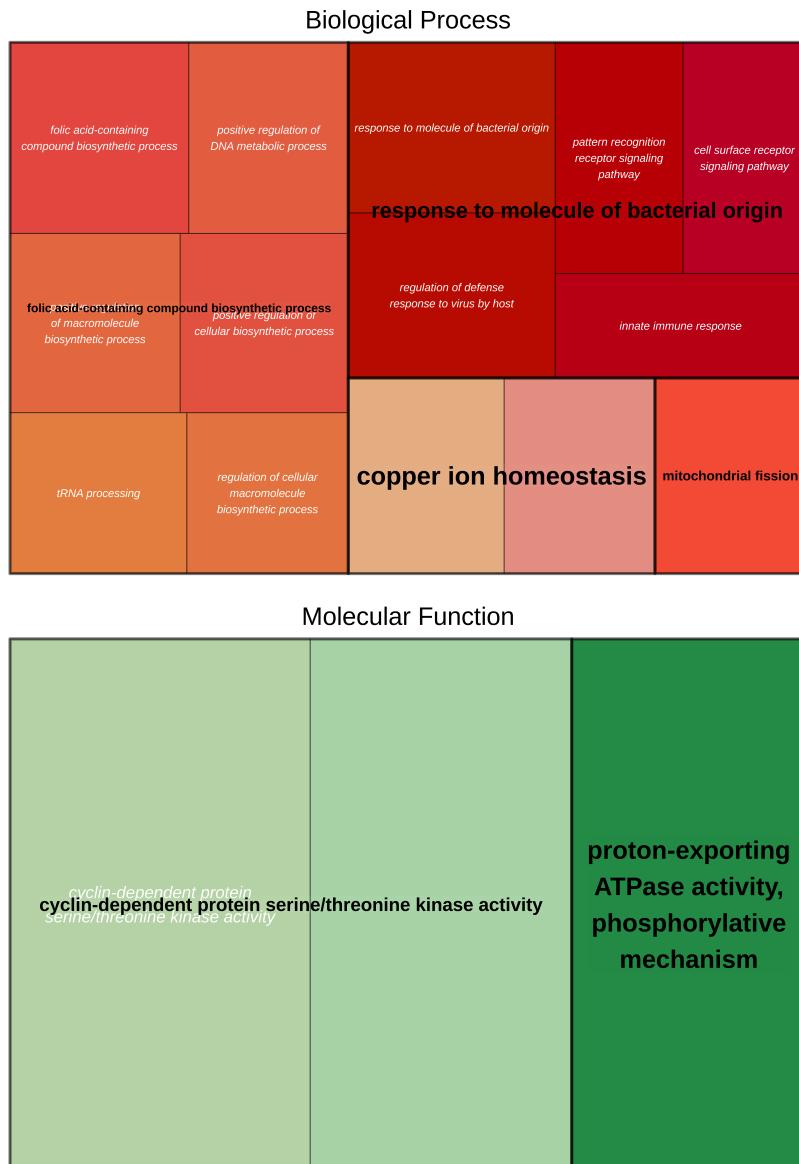
Results summary (number of genes and GO terms enriched for each dependent variable) for wild vs domesticated Brassica *rapa*:

	DEGs	GO_terms
Domesticated_bias	2031	56
Wild_bias	1797	84
Unstressed_bias	8	15
Stressed_bias	16	14
Interaction	41	24

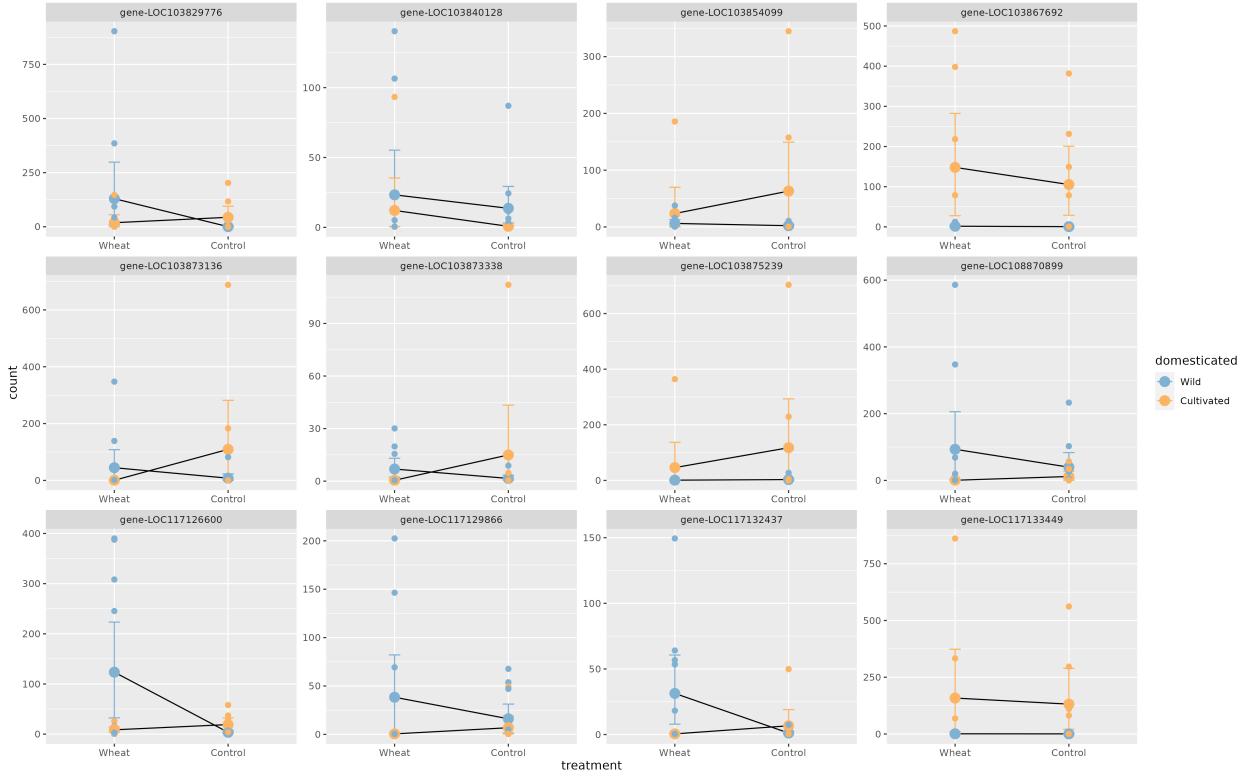
And the same analyses after excluding ssp. *tricoloris* outliers:

	DEGs	GO_terms
Domesticated_bias	572	52
Wild_bias	850	95
Unstressed_bias	4	18
Stressed_bias	7	20
Interaction	77	55

We can see from this that a great many genes are associated with domestication, but few with stress. 41 genes show an interaction between treatment and domestication, and are therefore of particular interest. Summary of the 25 GO terms associated with these interaction genes:



We can also plot these interaction terms to get a better idea of what the reaction norms look like for wild and domesticates accessions respectively:



Eyeballing these plots, there's no obvious trend in terms of increases or decreases in plasticity for wild vs domesticated accessions. Let's run statistical tests to check whether this is actually the case:

```
## [1] "Interaction genes with higher plasticity in wild: 17"
```

```
## [1] "Interaction genes with higher plasticity in domesticate: 24"
```

	Chi.squared	Paired.Wilcoxon	Paired.t.test
p-value	0.274	0.221	0.786

These results are non-significant, suggesting that genes have not changed systematically in their plasticity in the course of domestication. However, here we've combined the domesticated subspecies *B rapa* tricolouris and *B rapa* chinensis, which we know to be relatively distinct. Let's try re-running the analysis using subsets of the two domesticated subspecies separately:

	up_wild	up_dom	chisq	t	wilcox
tricolouris	35	6	5.90e-06	0.0984	0.0013884
chinensis	17	24	2.74e-01	0.0681	0.0293963

This is interesting: when we subset by the domesticated subspecies, we do get significant results for at least some of the statistical tests: it seems that wild *rapa* is more plastic than tricolouris, but may be less plastic than chinensis.

Raphanus gene expression

Results summary (number of genes and GO terms enriched for each dependent variable) for wild vs domesticated Raphanus:

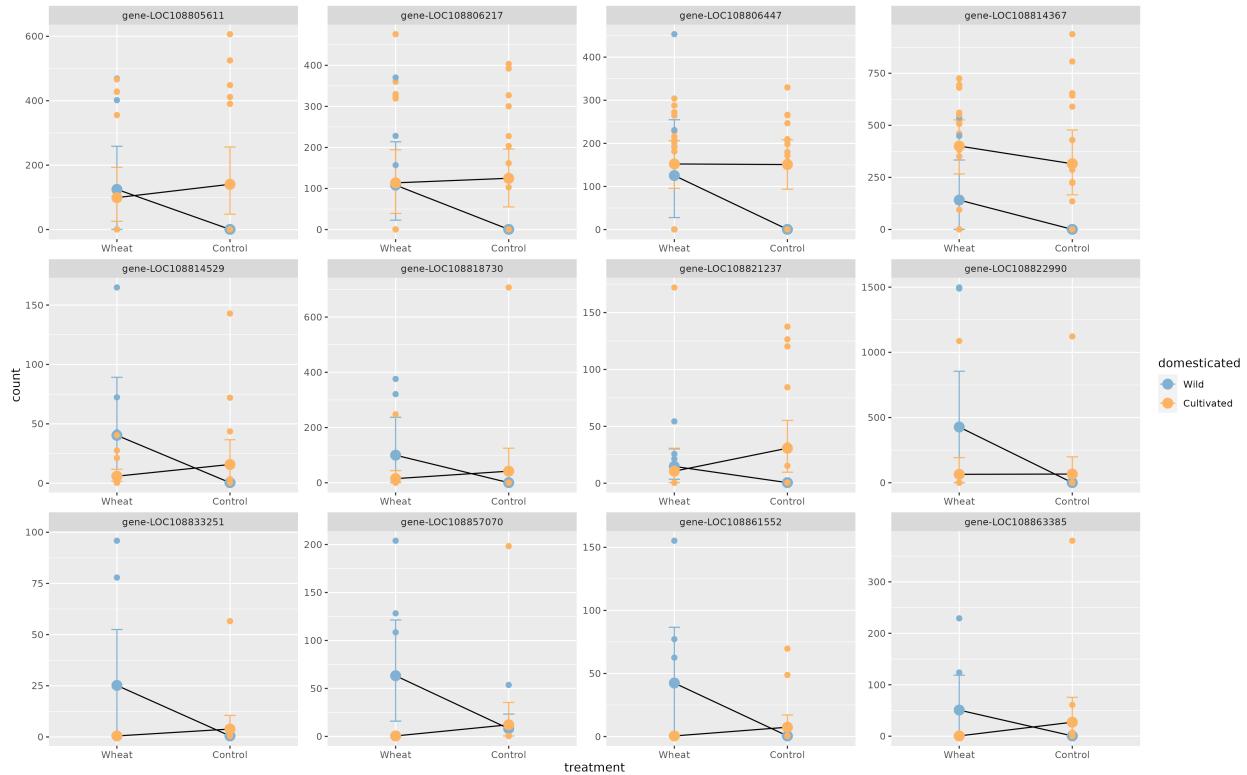
	DEGs	GO_terms
Domesticated_bias	526	47
Wild_bias	171	62
Unstressed_bias	76	34
Stressed_bias	52	27
Interaction	95	49

And the same analyses after excluding ssp. caudatus outliers:

	DEGs	GO_terms
Domesticated_bias	440	61
Wild_bias	169	68
Unstressed_bias	82	31
Stressed_bias	48	34
Interaction	85	47

Compared to Brassica, we find that fewer genes are associated with domestication, but more with stress. 98 genes show an interaction between treatment and domestication, and are therefore of particular interest. Summary of the 49 GO terms associated with these interaction genes:

We can also plot these interaction terms to get a better idea of what the reaction norms look like for wild and domesticates accessions respectively:



Eyeballing these plots, it looks like wild accessions tend to exhibit higher gene expression plasticity than domesticated accessions. Let's run statistical tests to check whether this is actually the case:

```
## [1] "Interaction genes with higher plasticity in wild: 69"
## [1] "Interaction genes with higher plasticity in domesticate: 29"
```

	Chi.squared	Paired.Wilcoxon	Paired.t.test
p-value	5.33e-05	4.5e-06	0.15

While the t-test is less conclusive, both the chi-squared and paired Wilcoxon tests strongly suggest that plasticity is higher in wild accessions than in domesticated ones. However, this result might be misleading, because the values for the Raphanus domesticates combine multiple different species, which may have resulted in depressed estimates of gene expression plasticity. For a more robust analysis, we need to run the analysis for each Raphanus domesticate individually.

species	up_wild	up_dom	chisq	t	wilcox
Raphanus raphanistrum munra	59	39	0.043400	0.0484	0.0008655
Raphanus sativus	67	31	0.000276	0.0928	0.0005876
Raphanus sativus var. caudatus	66	32	0.000594	0.7170	0.0002253

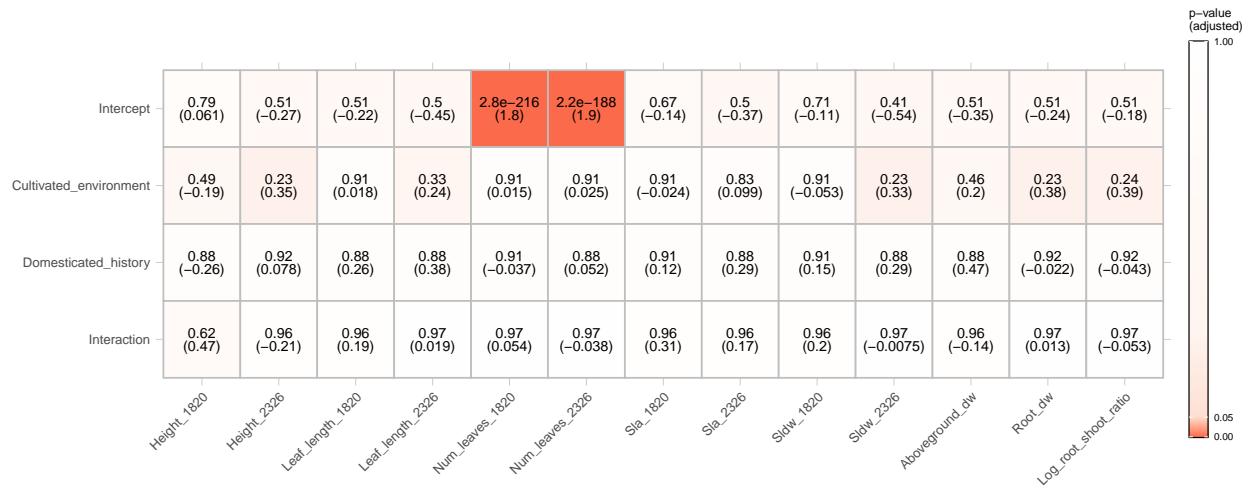
Again, while the t-test results are less conclusive, per the Wilcox and Chi-squared tests it's clear that for interaction genes plasticity is higher overall in the wild progenitor than in modern domesticates. We must therefore conclude that domestication has selected for decreased gene expression plasticity in radishes.

Brassica phenotypic expression

Here, we perform a similar analysis to above but using phenotypic traits instead of genes as the response variable. In each case we use a gaussian linear model, except for leaf number which is analysed using a Poisson model since it's a discrete trait. Here we include random effects, so the model design is:

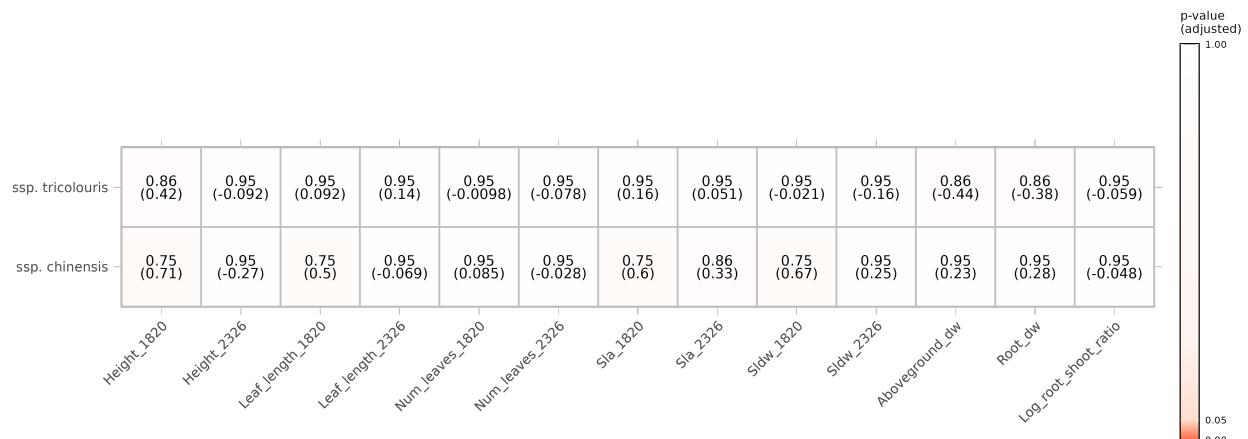
$$\text{expression} \sim \text{domestication} + \text{treatment} + \text{domestication*treatment} + (\text{1|population}) + (\text{1|parental standardization status})$$

Here we plot the p-values and coefficients (in parentheses) for each independent effect for each trait. FDR correction is applied across each row and response variables are scaled prior to analysis, again with the exception of those modeled using a Poisson distribution.

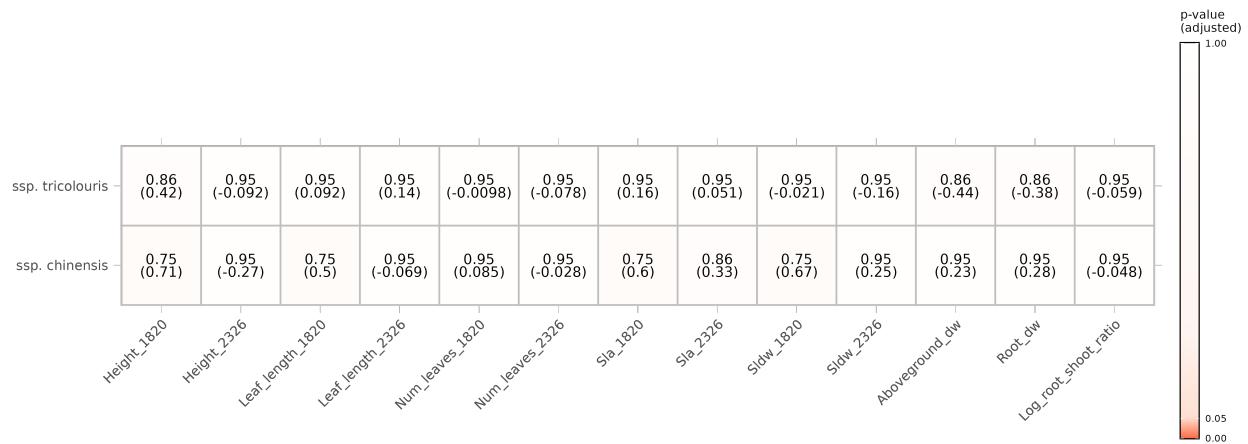


Our primary interest is in the bottom row, since significant terms here will indicate traits that exhibit differential plasticity in domesticated vs wild rapa. However, none of these interaction terms are significant. Nor, indeed, are any traits significantly different between wild and domesticated rapa overall, which is very surprising! One possibility is that the reason we're not seeing any effect is that we've combined two domesticated subspecies that we know to be fairly distinct: *B. rapa chinensis* and *B. rapa tricolouris*. What if we subset by these subspecies and re-run the analysis?

The interaction terms:

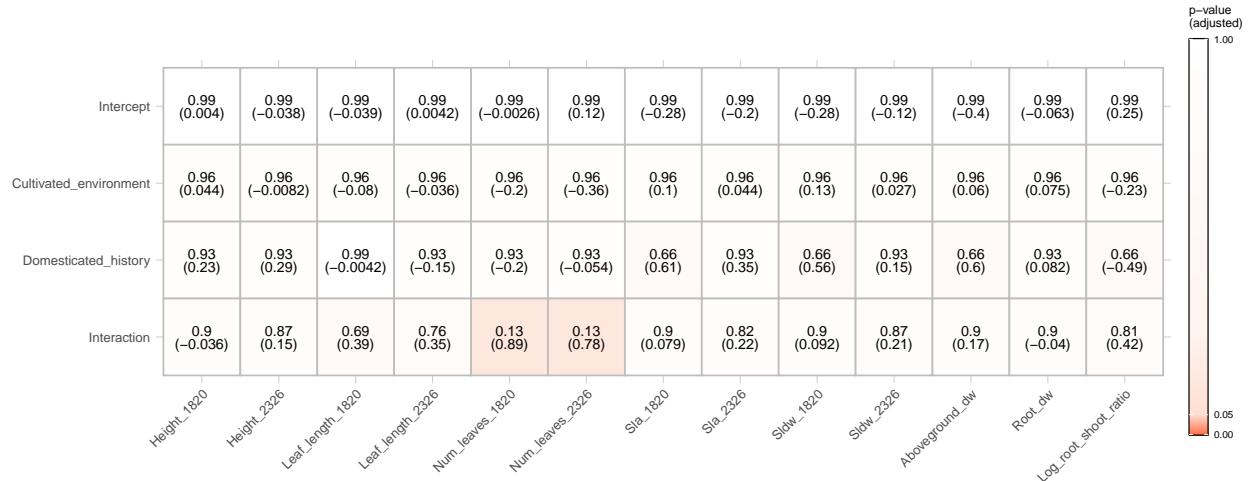


The wild vs dom terms:

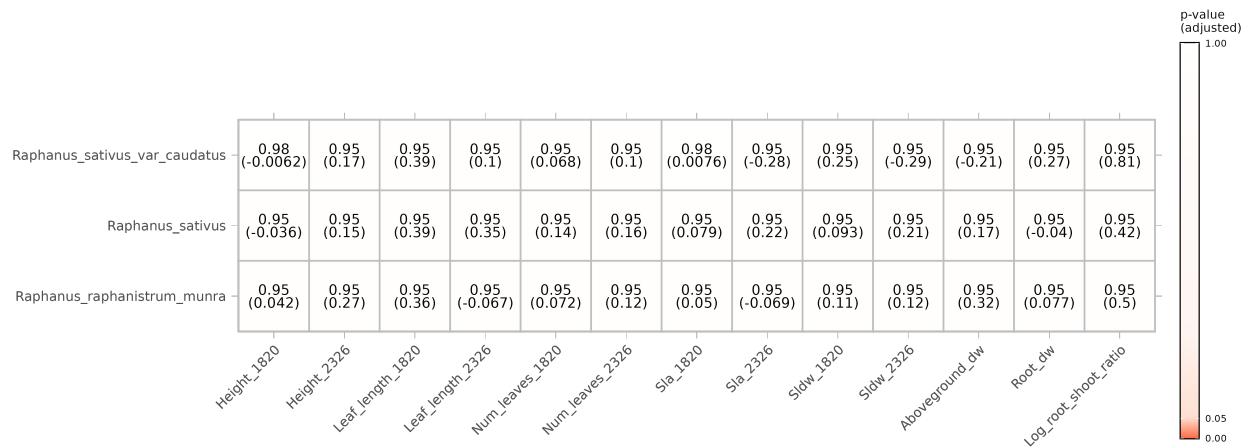


Even subsetting, we find no significant terms, so we're forced to conclude that none of the traits examined have shifted in their overall expression nor in their plasticity in the course of *Brassica rapa* domestication.

Raphanus phenotypic expression



Again, we reach the unfortunate conclusion that there seem to be no significant terms in any of the models. Might we find some if we subset by the separate *Raphanus* domestics, rather than combining them all into one? Below we plot the interaction terms only for each comparison:



To the contrary, subsetting by domesticate further erases any traces of interaction significance that we might have found for *Raphanus* (not least because we have to apply FDR correction over $3 \times 13 = 39$ comparisons here).

We must therefore conclude that domestication hasn't selected for greater phenotypic plasticity in domesticates relative to their wild progenitors.

Work package 2: Comparing wild progenitors to never-domesticated wild species

We now wish to ask a different question: do 'progenitor species' (i.e. those that were the original targets of human selection) differ systematically in their patterns of gene and phenotypic expression from wild species that were never domesticated? We are particularly interested in knowing whether progenitor species express greater phenotypic plasticity than their never-domesticated relatives, since this could suggest that early human farmers either intentionally or inadvertently targeted species that were particularly receptive to the benefits of cultivation. Unfortunately, for *Raphanus* we have no data for non-domesticated wild species, so this analysis will be restricted to Brassica, comparing wild *Brassica rapa* to a number of never-domesticated Brassicas.

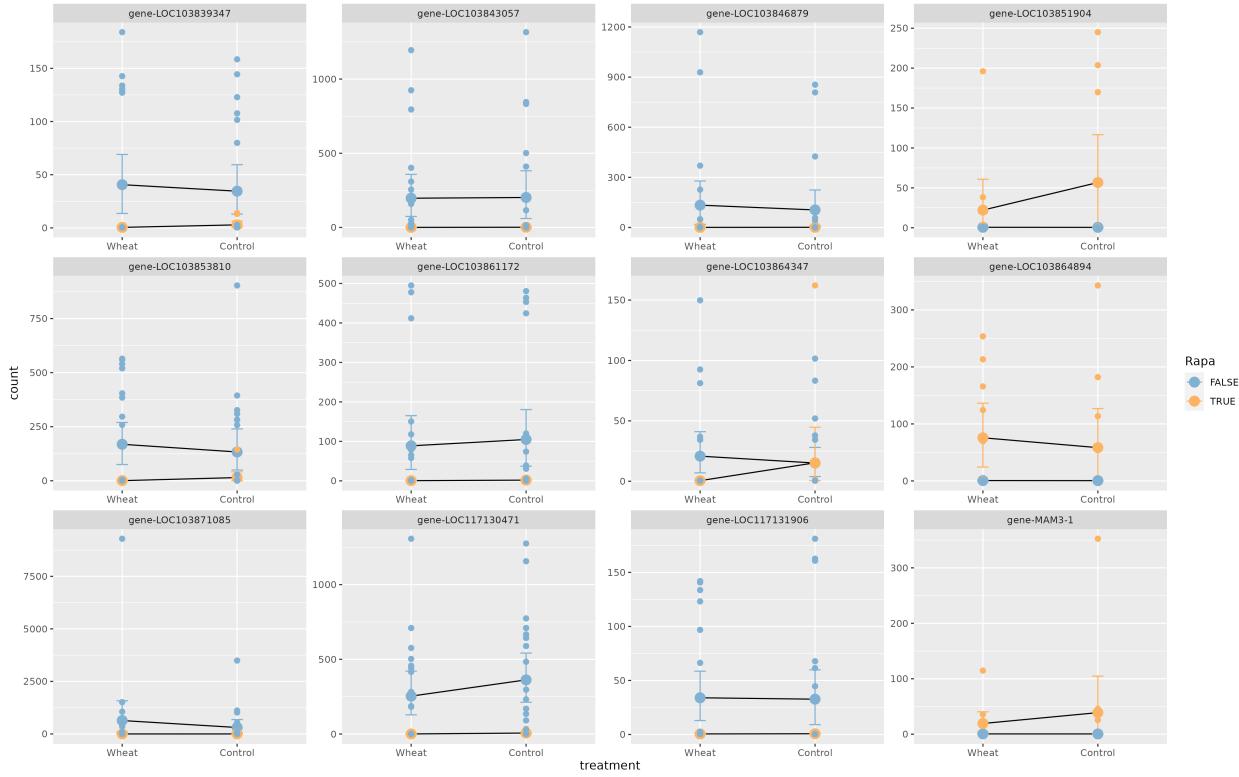
Gene expression

We'll begin with the results of a DESeq2 model as before, except that instead of comparing wild to domesticated, we'll compare progenitors (wild *Brassica rapa*) to non-progenitors (all other wild Brassicas).

	DEGs	GO_terms
Domesticated_bias	8710	53
Wild_bias	9520	75
Unstressed_bias	9	40
Stressed_bias	11	10
Interaction	63	30

The results here are similar to those we generated when comparing the wild and domesticated *Brassica rapa*: many genes dividing the different species, few differing with treatment, and a mid-sized number with

interaction terms. Again, our primary interest is in these interaction genes, since these are those that show differential plasticity between the progenitor and its never-domesticated relatives. Plotting the 12 genes with the lowest p-values for this comparison:



Eyeballing these plots, there's surprisingly little difference in the reaction norms for progenitor and non-progenitor accessions, so it seems likely that the effect sizes we're observing here are quite low despite the small p-values. Nonetheless, we can check whether there's an overall trend in terms of increases/decreases in plasticity between the two groups:

```
## [1] "Interaction genes with higher plasticity in progenitor: 36"
```

```
## [1] "Interaction genes with higher plasticity in other wilds: 27"
```

	Chi.squared	Paired.Wilcoxon	Paired.t.test
p-value	0.274	0.221	0.786

We find no effect here, but recall that this analysis combines multiple different wild Brassicas, which could depress any effect sizes we find. To be certain, we now subset by wild Brassica species:

species	up_otherwild	up_progenitor	chisq	t	wilcox
Brassica montana	35	28	0.3780	0.333	0.1311542
Brassica cretica	31	32	0.9000	0.809	0.6538502
Brassica macrocarpa	32	31	0.9000	0.658	0.2543378
Brassica rupestris	25	38	0.1010	0.894	0.2216964
Brassica incana	24	39	0.0588	0.431	0.3571543

species	up_otherwild	up_progenitor	chisq	t	wilcox
Brassica villosa	29	34	0.5290	0.848	0.9918065

Even when subsetting, it's clear that there is no overall trend for the Brassica progenitor species to have higher or lower gene expression plasticity in interaction genes when compared to never-domesticated Brassicas.

Phenotypic expression

What about phenotypes- does wild B rapa exhibit increased phenotypic plasticity relative to its never-domesticated relatives, upon which human ancestors might have selected?

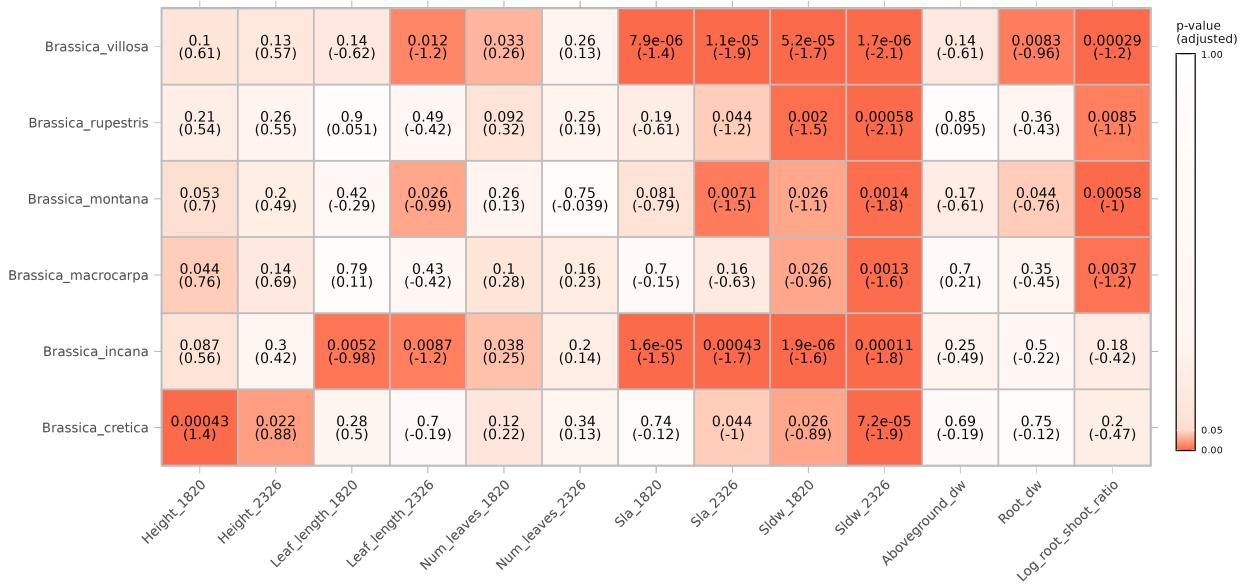


Here we see a more interesting set of results: many traits differ between wild Rapa and the other wild species, and a few traits have near-significant interaction terms: height, above-ground dry weight, and root dry weight. Perhaps these interaction terms will become more clearly significant (or non-significant) if we subset the never-domesticated wilds by species instead of combining them all into one?



Alas, to the contrary: when we subset, we lose any hint of significance in the interaction terms. Note that these values will once again have been hit hard by FDR correction, since we have to correct for $13 \times 6 = 78$ comparisons. Nonetheless, we're forced to conclude that *Brassica rapa* was not selected for its uniquely high plasticity at the level of either gene expression or phenotypic expression.

We did, however, see significant differences between *B. rapa* and other wild Brassicas in terms of overall expression of many traits. Let's plot the coefficients of these comparisons when subsetting by species, to see if there are any consistent trends in terms of wild *rapa* being e.g. larger or leafier than its never-domesticated relatives. The values in parentheses below are the actual coefficients: negative values indicate that wild *rapa* exhibits lower trait values than the never-domesticated wild species, and positive values the converse.



The most mobvious effect here is that wild *Brassica rapa* seems to generally have lighter, smaller leaves than its wild relatives, which seems surprising! It also has a significantly lower root-shoot ratio than most other examined species.

Work package 3: Comparing generation 4 to generation 2

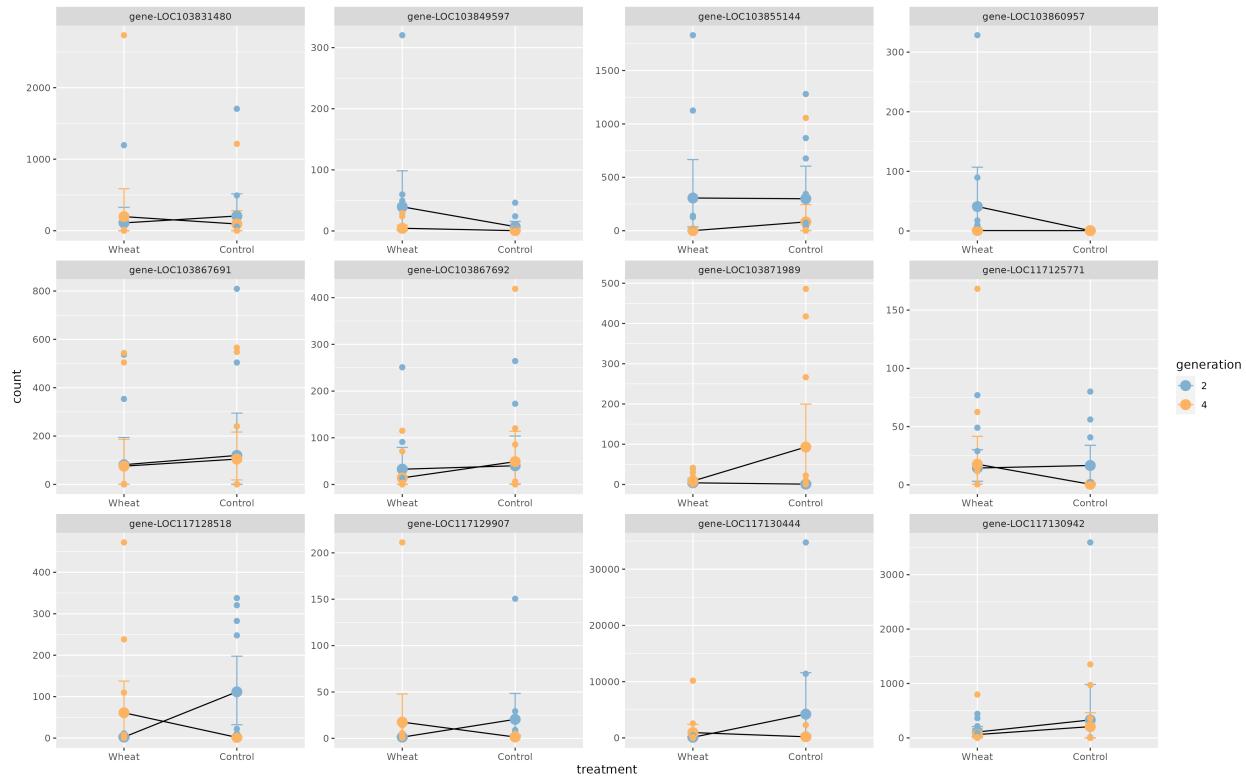
Another question we can ask regards the changes we observe when rearing plants over many generations. This is very much a WIP, but a preliminary question is whether, when performing a plasticity analysis similar to those performed above for WPs 1 & 2, we see greater (or lesser) degrees of plasticity for plants in generation 4 vs plants in generation 2.

To test this, we subset to only those gen2 accessions which have a matching accession represented in the gen4 RNAseq data, and then we run the following DESeq2 model:

$$geneexpression \sim generation + treatment + generation * treatment$$

Brassica

For Brassica, this analysis yields only 12 interaction genes. Plotting these, we don't see a strong signal of increased or decreased plasticity:



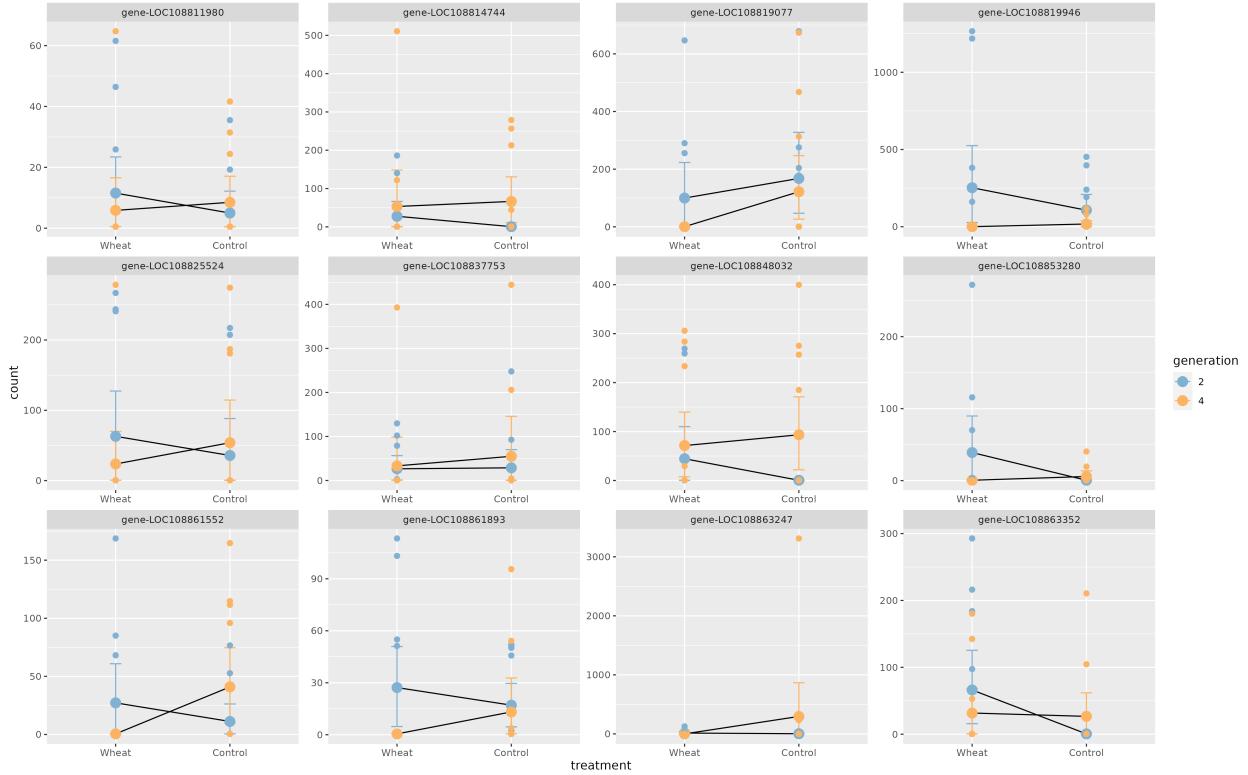
Statistical tests here are indeed non-significant, but do recall that we have little power here due to the small sample size of interaction genes:

```
## [1] "Interaction genes with higher plasticity in generation 4: 4"
## [1] "Interaction genes with higher plasticity in generation 2: 8"
```

	Chi.squared	Paired.Wilcoxon	Paired.t.test
p-value	0.248	0.129	0.108

Raphanus

For Raphanus, we have a more promising number: 52 interaction genes. Plotting the top 12 of these:



It looks like plasticity might be higher on average in gen2, but unfortunately this isn't borne out in the stats:

```
## [1] "Interaction genes with higher plasticity in generation 4: 24"
## [1] "Interaction genes with higher plasticity in generation 2: 28"
```

	Chi.squared	Paired.Wilcoxon	Paired.t.test
p-value	0.579	0.946	0.28

Thus, the conclusion from this preliminary analysis is that there has been no systematic increase or decrease in gene expression plasticity between generations 2 and 4 for Brassica.