**Accessories dominate the costs of producing seed**

**E. H. Wenk\* a, K. Abramowiczb, M. Westoby a, D. S. Falstera**

a Department of Biological Sciences, Macquarie University NSW 2109, Australia

b Department of Mathematics and Mathematical Statistics, Umeå University, 90187 Umeå, Sweden

\* Corresponding author

Email addresses: ehwenk@gmail.com, konrad.ab@gmail.com, mark.westoby@mq.edu.au, adaptive.plant@gmail.com

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# Abstract

accessory costs are BIG

in failed or surplus ovules more so than in costs of success

one consequence is that seed output radically underestimates RE and is only weakly correlated

prodn of surplus ovules is tied up with overall strategy, and correlates with propagule size

[general comment: these are all at some level costs of sex -- at face value, a selfing or apomictic species would not need to produce any surplus ovules, plus would not need showy flowers -- accessory costs would be strictly fruit and seed-coat structures for successfully-provisioned seeds]

# Introduction

Plants allocate a sizeable proportion of their photosynthetic energy to reproduction (refs? including Wenk & Falster, 2016), including to seeds and also into the many other tissues associated with reproduction, termed accessory costs. Accessory costs include energy required to form a successful seed (e.g. flower petals, seed pod, and dispersal tissues) and energy lost via aborted buds, flowers and fruit (see Table 1 for summary of terms). Previous studies show that for perennial species anywhere from 15% – 99% of total reproductive investment may go into accessory costs (Haig & Westoby 1988; Henery & Westoby 2001; Lord & Westoby 2006). Moreover, since fruit set and seed set is generally below 50% in perennial species (Stephenson 1981; Sutherland 1986; Knight *et al.* 2005; Rosenheim *et al.* 2014), the cost of aborted tissues may be substantial. Yet, despite being a significant energy sink in ecosystems, and with exception of a few well-studied species (refs), little is known about the allocation of energy among different reproductive tissues across the plant kingdom.

While plant species demonstrate an extraordinary diversity of reproductive structures and strategies, the investments made by most species fall into several broad categories (Figure 1). ... Combined, these different activities suggest XXX main types of investment, as summarised in Figure 1.

There are multiple reasons to expect not only that investments into these different types of accessory cost will be substantial, but also that the relative amounts might differ during ontogeny and among species. Evolutionary arguments would suggest plants evolve to optimize the amount of accessory costs per successful seed (refs??). Some investment is undeniably beneficial for the successful formation and dispersal of a seed. Without showy petals insects would not be attracted to the stamens and stigma, without sepals the developing bud would not be protected, without a seed coat a seed would not be protected during dispersal, and without a tasty fruit, many seeds would not be dispersed. At the same time, there are surely diminishing returns in the benefits accrued through greater investment in accessory costs, especially given that energy invested in accessory costs detracts from further seed production. There will therefore be an optimal level of investment per seed. Moreover, this optimal investment is likely to differ among species, depending on their specific physiologies and interactions with pollinators.

This notion of an optimal investment in accessory tissues also suggests some systematic variation in accessory costs among species, arising from differences in pollen-to-ovule ratio, seedset and seed size. Haig & Westoby (1988) developed a conceptual model for the relative allocation of energy to different reproductive tissues, dividing the total energy investment per seed between the costs of attracting pollen versus the cost of provisioning pollinated ovules. Their simple model makes several predictions, including that plants 1) produce excess ovules and flowers to optimize seed production across a population and across time, 2) face a trade-off between pollen attraction and ovule provisioning, and 3) allocate just enough to pollen-attracting tissues to ensure pollination of the number of ovules they are able to provision. This initial model has since been extended to account for the proportion of energy invested in pollen attraction versus seed provisioning tissues (Rosenheim *et al.* 2014, 2016; Burd 2016). These studies indicate that species with relatively low pollen-attraction costs should display parental optimism: an overproduction of ovules, relatively few of which mature in an average year due to limited resource supply. In contrast, species with higher pre-pollination costs should display parental pessimism: an underproduction of ovules, with ovule number limiting seed production in many years (Mock & Forbes 1995; Burd 2008; Rosenheim *et al.* 2014). Generally, parental optimists will abort a large number of less costly flowers (i.e. have high XXX costs), while parental pessimists will abort a relatively smaller number of more costly flowers. In addition, …something about amount of provisioning should differ among optimists and pessimists …? Moreover, a tendency towards over- or under-production of ovules will be exacerbated by environmental stochasticity, because plants will invest more heavily in the cheaper of the tissue categories (Rosenheim *et al.* 2010, 2014). In addition, high individual variation in pollen receipt will cause increased investment in flowers (Burd 2008; Burd *et al.* 2009; Schreiber *et al.* 2015) and an increased number of ovules per flower (Burd 1994).

Extending these ideas around parental pessimists and optimists from Rosenheim et al (2014), leads to XXX specific hypotheses for the current study (Fig. 2). Across angiosperm species, total per seed accessory costs have been shown to scale approximately isometrically with seed size (Henery & Westoby 2001; Moles, Warton & Westoby 2003; Lord & Westoby 2006, 2012; Chen, Felker & Sun 2010). In other words, to first order, the relative energy expenditure on accessory costs does not vary systematically with seed size across species. How these accessory costs are divided between different tissues, however, is expected to vary systematically with seed size. Specifically, …

are captured and extended in the schematic Fig 2, which can be considered one of the working hypotheses for the present paper. Beginning at the box labelled “parental optimist”, such species by definition produce an overabundance of ovules, relative to their ability to provision pollinated ovules to mature seeds. Such plants will be selected to evolve relatively smaller flowers, since producing a large number of excess flowers and also having those flowers individually costly is plainly a disadvantage. The complement to this argument is that these species will have higher provisioning costs, relative to their pre-pollination costs. A second line of reasoning also links the parental optimist with higher provisioning costs: a benefit of having an excess of pollinated ovules, relative to the likely ability to provision them, is that the parent plants can select for offspring with the most vigorous genotypes, aborting the remaining embryos shortly after pollination (Figure 2). In turn, having been able to choose the best embryos, the parents should invest more heavily in provisioning, providing the embryos with the greatest probability of success. Meanwhile, big-seed species should also be selected to have relatively higher provisioning costs, as ###. A further logical consequence is that parental optimists should have lower seedset in an average year, due to the large number of ovules that are aborted (Figure 2). In summary, Fig 2 illustrates how different feedback loops are expected to reinforce each other and produce coordinated variation in pollen-ovule ratio, pre-pollination costs versus provisioning costs, and year-to-year variation in pollination success. No previous studies have looked at how the per successful seed *cost of pre-pollination failure* scales with seed size, but for the species considered by Lord & Westoby (2006, 2012) total pre-pollination costs per seed scaled isometrically with seed size. We predict that both the pre-pollination failure costs and post-pollination failure costs will scale isometrically with seed size.

In addition to the species-level shifts in total accessory costs and investment in specific accessory tissues, individuals within a species may shift their investment patterns as they grow and age. If accessory costs shift with reproductive effort (RE), plant size or plant age, then individuals should be selected to shift their timing of reproduction to minimize accessory costs and to increase propagule production from a given energy investment. Kelly (1994) lists as one potential explanation for masting the reduction in accessory costs, indicating that if accessory costs were lower in individuals of a species with higher RE, plants would be selected to have fewer, larger reproductive episodes. We do know that RE increases with plant size (or age) (Obeso 2002; Weiner *et al.* 2009; Wenk & Falster 2015), but not how the balance between seed versus accessory costs shifts.

A detailed look at where investment in reproductive tissues within and among species is therefore warranted. In this study, we ask the following questions:

1. How much do species invest in different reproductive tissues and does this differ among species?
2. Does total reproductive investment scale isometrically with seed size, as has been previously suggested?
3. Across species, does investment in XXX increase with seed size, and decrease with XXX, as hypothesised?
4. Within a species, do total accessory costs or particular accessory cost components shift with plant size, age, or reproductive investment?

The dataset we use to address these questions is, to our knowledge, the most complete dataset that simultaneously measured plant size, vegetative investment, reproductive investment, seed investment, seed count, and seed mass across multiple species at different size and ages in a native community. In a recurrent-fire coastal heath community, we studied fourteen species differing in seed size, lifespan, and maximum height. Individuals were sampled at different ages across a fire-created chronosequence, from 3 months to 30 years. We assessed total reproductive investment every 3 weeks for a year, to determine total investment both in tissues that developed into mature seeds and in tissues that were aborted during the developmental trajectory. This detailed accounting allows us to investigate correlates of reproductive investment across and within species.

Finally, given the complexity of measuring all the components of reproductive investment, we assess how well different surrogate measures potentially predict total reproductive investment? For this purpose we consider total seed weight, total fruit weight, and total pre-pollination investment.

# Methods

## Study system

The study was carried out in Kuring’gai National Park, just to the northeast of Sydney, Australia. The sandstone ridges throughout the park host a coast heath community, whose dynamics is governed by fire. Average intervals between fires are in the range X-XX years (from fire maps kept by NSW NPWS). The community includes perennial species that re-sprout following fire and also obligate seeders, species that are killed by fire and re-establish from seed. The obligate seeders included in this study germinate within a year of the fire and often after the next rain. Since the fire history of the park is well documented, the age of obligate seeders at a site can be estimated. In total, we selected 14 obligate-seeder, woody perennials that are common in the community, with asymptotic heights ranging from 0.5m – 5 m. They were *Banksia ericifolia* (Proteaceae), *Boronia ledifolia* (Rutaceae), *Conospermum ericifolium* (Proteaceae), *Epacris microphylla* (Ericaceae), *Grevillea buxifolia* (Proteaceae), *Grevillea speciosa* (Proteaceae), *Hakea teretifolia* (Proteaceae), *Hemigenia purpurea* (Lamiaceae), *Leucopogon esquamatus* (Ericaceae), *Persoonia lanceolata* (Proteaceae), *Petrophile pulchella* (Proteaceae), *Phyllota phylicoides* (Fabaceae), *Pimelea linifolia* (Thymelaeaceae), *Pultenaea tuberculata* (Fabaceae). The family Myrtaceae is well represented in the community, but absent from the study, as all common species in this family re-sprout following fire. All sites were chosen to have minimal *Eucalyptus* cover, such that *Banksia ericifolia*, *Hakea teretifolia*, and *Allocasuarina distyla* (not included in our study because it is dioecious) would be the dominant canopy species late in succession, at heights of 3-5 m.

## Field measurements

The study was conducted over a single year, with the initial plant measurements and subsequent harvest conducted during the late autumn and early winter, the period of minimal vegetative growth in this plant community, and repeat visits made throughout the year to record reproductive activity. Individuals were sampled at different ages across a fire-created chronosequence, from 3 months to 30 years. Site ages were estimated from fire records maintained by NSW NPWS. At the conclusion of the study, the approximate ages of the individuals on the six sites were: 1.4, 2.4, 5, 7, 9 and 31 years. Plants were tagged during May-June 2012 and harvested during May-June 2013, with a given individual tagged and harvested within 2 weeks of the same calendar date. Only one species, *Persoonia lanceolata*, displayed any shoot extension during these months. These months are similarly a period of minimal reproductive activity – only *Banksia ericifolia*, *Grevillea speciosa,* and (occasionally) *Hemigenia purpurea* flowered during this period – although a number of species had immature fruit from the previous year (*Persoonia lanceolata*) or small buds that would open in the subsequent year (*Boronia ledifolia*, *Conospermum ericifolium*, *Epacris microphylla*, *Grevillea buxifolia*, *Grevillea speciosa*, *Leucopogon esquamatus*).

Seven healthy individuals of each species were selected at each site (and thus age). At the beginning of the study year, a sketch map of the main axis of the plant and all side branches from the main axis was made. The length of each stem segment along the main axis, and sometimes of side branches, was recorded. The basal diameter of each stem segment was recorded, approximately 10 mm above the node to avoid the nodal swelling. The number of leaves along each stem length or the length of stem covered in leaves (for species with numerous small leaves covering the branch in a regular pattern) was recorded. At the end of the study year, the maps were amended to show the year’s growth. The diameter of all stem segments was remeasured, the length of and leaf number on new shoots along the main axis were added, and the loss of leaves was noted. The plants were then harvested at ground level. Each plant was sub-divided into multiple segments along the main axis. The plant parts were oven dried at 60ºC for at least 1 week. Leaves and stems were separated and weighed for each of the nested stem segments, such that stem width versus biomass could be calculated for each successive segment marked along the main axis.

Flowering parts on all individuals were recorded during repeat censuses, every four weeks during cooler months and every three weeks during spring and summer. At each census, all flowering parts were counted, including buds (by size class), flowers, young fruit, and mature fruit. For some species the size of immature and mature fruit and cones was also measured, as the final size of the fruit was quite variable. The exact flowering parts considered varied considerably by species due to their diverse floral structures. Flowcharts detailing what flower parts were included for each species are provided in Appendix ###. Appendix ### also includes a table that indicates how each flowering part was measured for each species. Each of the flower parts was independently collected from multiple untagged individuals in the community to determine its dry weight.

## Calculating total reproductive investment

Total reproductive investment is the sum of investment in all the different flowering parts during the year (Fig. 1). Reproductive investment can be further divided into investment into propagules (seeds or seeds and attached fruits) versus accessory tissues. Accessory tissues include aborted structures (including both aborted flowers and fruit), structures used for pollination (i.e. successful flowers), and structures used for packaging and dispersal (including cones and some seed pods).

and the developmental progression of these flowering parts is included in

Mention that the species included are all recorded [?] as producing a consistent number of ovules per flower.

Details: A document, for the supplementary materials, describing the methods should be out next priority.

## Statistical methods

For slope tests, are you using regression or SMATR? Should be the latter.

# Results

## Accessory costs and accessory cost components

Of the 599 plants included in this study, 223 individuals produced at least one seed during the year. Across these individuals, on average 91% of reproductive investment went to accessory tissues rather than to propagules, rising to 96% if only embryo and endosperm were treated as direct investment in offspring, with seed coats and dispersal structures attributed to accessory costs. Across species, accessory costs (versus embryo and endosperm) ranged from a low of 91.9% for *Pimelea linifolia* to a high of 99.8% for *Hakea teretifolia* (Table 2).

Total accessory costs can be divided broadly into costs of failure (the weight of all aborted parts, including mature flowers that fail to set seed) versus costs of success (seed weight plus the total per ovule cost of required floral parts, both pre- and post-pollination). Only the two cone-bearing species, *Banksia ericifolia* and *Petrophile pulchella* had greater investment in successful tissues than in failed tissues. Three species, *Hakea teretifolia*, *Phyllota phylicoides*, and *Pultenaea tuberculata* spent more than 90% of their reproductive investment on failed tissues (Table 2). For most species, these failed tissues were predominantly pre-provisioning, with aborted seeds and fruit a minor component (Table 2). Note that fruit that abort after pollination but before provisioning are recorded as shed flowers, such that the pre-provisioning category includes ovules that are aborted both due to lack of pollination and due to early maternal selection.

Seedcosts are further divided into three investment pools: seed mass, mass of parts formed up to the point of pollination (on a per ovule basis), and the mass of packaging and dispersal structures (on a per ovule basis). The relative costs of these components shifted markedly across species (Figure 3). Four species, *Epacris microphylla, Hemigenia pupurea, Pimelea linifolia, and Pultanaea tuberculata* had pre-pollination costs that were greater than 50% of total seedcosts, while 5 species had pre-pollination costs that were less than 10% of total seedcosts (Table 3). The proportion of energy invested in packaging and dispersal tissues ranged from a low of 0.14 (for *Hemigenia pupurea*) to a high of 0.98 (*Banksia ericifolia*) (Table 3). Importantly, the maximum any species invested in seeds was less than 25% of total energy expenditure.

## Correlations between seed size and accessory costs

Total accessory costs and accessory cost components correlated with seed size. Total accessory costs per seed increased isometrically with species’ mean seed size (slope=1.236 ±0.283, not sig diff from slope of 1 at pslope.test=0.0934) (Table 4, Figure 4a). The other two components of total seed costs did not scale 1:1 with seed size – required pre-pollination costs had a slope significantly < 1 (slope=0.638±0.203, pslope.test=0.0022), indicating that larger-seeded species invested relatively less in pre-pollination tissues (Figure 4c). In contrast, packaging and dispersal costs increased more rapidly than seed size, with a slope significantly > 1 (slope=1.420±0.371, pslope.test=0.0293) (Figure 4b). Both total costs of failure and the pre-pollination versus provisioning components scaled isometrically with seed size (Table 4).

## Correlations between seed size and seed set

Seed size was also significantly correlated with seedset: species with larger seeds had lower seedset (Figure 5a, r2=0.56, p=0.0022). This decline in seedset is also apparent in Figure 5b, which shows bud and seed counts, scaled to leaf area, plotted against seed size. Larger-seeded species produced disproportionately many buds, such that the slope of the relationship between number of buds versus seed size was much shallower than -1 (slope=-0.673±0.074, pslope = -1=<0.0001). However, larger-seeded species also aborted a disproportionately large number of buds and the slope of the regression between scaled seed versus seed size is somewhat steeper than -1 (slope=-1.190±0.097, pslope = -1 =0.0002). The large-seeded, low seedset species are also those with proportionally lower pre-pollination costs (Figure 5c, Table 4).

## Shifts in accessory costs with other factors

Within each species, per seed accessory costs decreased with increasing seedset (Table 5). For five species the decrease in accessory costs was proportional to the increase in seedset, while six had a slope that was significantly greater than -1 (closer to 0) and three had a slope that was significantly less than -1 (further from 0) (Table 5).

## Shifts in accessory costs with plant size, age, or reproductive effort

None of these species demonstrated the hypothesized decrease in per seed accessory costs with increasing plant size or RE, with only 3/39 tests between reported in Table 6 were significant, these may represent little more than chance.

. Instead, the only significant correlations are in the reverse direction: *Epacris microphylla* individuals that were larger and those with higher RE had slightly higher per seed accessory costs (Table 6). Two additional species (*Hemigenia purpurea* and *Leucopogon esquamatus*) showed shifts in accessory costs with age, with one other decreasing (*Boronia ledifolia*) (Table 6). Given that

## Correlates with total reproductive investment

Of the 599 plants included in this study, 357 individuals produced buds and 223 individuals produced mature seeds. Even among the individuals that produced seeds, propagule investment was only rather loosely correlated with total reproductive investment, both within and across species (Tables 6, 7 respectively). All but one species showed a significant correlation between the two metrics, but only two species displayed an r2 above 0.80 and only half the species had an r2 above 0.70. Furthermore, the slopes and intercepts of the relationship differed across species with the result that the correlation between reproductive investment and propagule investment across all individuals had an r2 of just 0.52 (Figure 6a).

To assess what approximation of reproductive investment was the best alternative to measuring total reproductive investment, we regressed additional investment categories against total reproductive investment. Measures that included only the costs of successful tissues, those associated with the production of mature seeds, were inferior predictors of total reproductive investment compared to measures that included investment in failed tissues (Table 7). In particular, note that the correlation between investment in all failed tissues versus all reproductive tissues was 0.94, while the correlation between investment in all successful tissues (seedcosts\*seed count) versus all reproductive tissues was just 0.71. Investment in failed tissues is a better predictor for two reasons. First, because failed tissues accounted for 81% of total reproductive investment; and second, because energy investment into buds and flowers was more predictable, while further filtering processes occur before buds become mature seeds. A composite metric, the count of buds initiated \* average flower mass, when regressed against total reproductive investment, had an r2 of 0.93, making it nearly as strong a predictor of total reproductive investment as failed tissue investment. This composite metric has the merits that it would be relatively easy to measure on large numbers of plants and that it effectively combines both the within and across species variation (Table 7, Figure 6b).

# Discussion

From introduction: Correlations have been observed for many of the direct pathways illustrated in Figure 2, as well as more broadly across different boxes. Big-seeded species do indeed have higher per-seed provisioning costs both to attract the animal dispersers and to protect their seeds during dispersal (Lord & Westoby 2006, 2012). This is in agreement with a strong correlation between seed size and biotic dispersal agents both in the fossil record (Moles *et al.* 2005; Eriksson 2008) and modern floras (Hughes *et al.* 1994). Worldwide, there is an observed decrease in seed set with increasing seed size (Moles & Westoby 2006).

Also add back material from intro on models.

Investment in seed dry mass represented a quite modest proportion of total reproductive investment for the 14 perennial species included in this study, with just 1-8% of reproductive energy going to propagules versus other reproductive tissues (Table 1). Even the individual with the lowest accessory costs invested just 15% of its reproductive energy into the embryo and endosperm itself. A similarly large expenditure on accessory costs has been shown for perennial species in other studies (Haig & Westoby 1988; Henery & Westoby 2001; Lord & Westoby 2006; Rosenheim *et al.* 2014). Dividing total reproductive investment into functional tissue categories illustrates the similarities and differences in energy allocation across these species, providing support for theories on patterns of total accessory investment (Lord & Westoby 2012) and the relative allocation to different reproductive tissue types (Haig & Westoby 1988; Rosenheim *et al.* 2014). Notably, larger-seeded species are parental optimists, producing an over-abundance of ovules relative to their ability to provision them in an average year, and investing proportionally more per seed in provisioning costs (versus pollen-attraction costs) (Figure 2).

A number of hypotheses have suggested greater reproductive effort should lead to compounding fecundity returns, decreasing accessory costs as a share of total reproductive costs (Myers & Doyle 1983; Sibly, Calow & Nichols 1985; Reekie & Bazzaz 1987a; Kelly 1994). This pattern was not observed in this dataset. Across individuals within a species, total accessory costs and accessory cost components did not shift consistently with plant size, age, or total reproductive investment.

The second major result from these data was that for perennial species with low seedset, total reproductive investment was best predicted by energy expenditure in buds and flowers, not by investment in seeds or fruit.

## Accessory costs are large

Many estimates of plant energy investment in reproduction do not account for total accessory costs (reviewed in Obeso 2002; Rosenheim *et al.* 2014; Wenk & Falster 2015). Including only investment in seeds or fruit or only a subset of accessory costs will substantially underestimate a plant’s total investment in reproduction (Table 1, Figure 1). For instance, a plant’s reproductive allocation, the proportion of energy spent on reproduction rather than on growing and replacing vegetative tissue, will be very substantially underestimated if investment in aborted tissues is omitted from calculations of total reproductive investment (Wenk & Falster 2015). Similarly, studies seeking to estimate the cost of reproduction, may reach erroneous conclusions if they record only shifts in seed production year upon year, ignoring investment in accessory tissues (Obeso 2002).

Some tissue types accounted for a far greater proportion of total reproductive energy investment than others, though species differed in their exact allocation patterns. [so here you first need to say which tissue types, before going on to diffs between species] The proportion of reproductive energy allocated to “success” versus “failure” was markedly different across species, broadly showing that species which allocated more of their energy to failure had lower seedset (r2=0.64, p=0.0010 for the relationship between seedset and proportion reproductive energy to failure when the largest cone-bearing species is omitted. *Banksia ericifolia,* with large woody cones, allocated disproportionately to success, relative to its seedset, due to the high cost of producing a mature cone; Table 1).

The majority of energy invested in aborted tissues went into buds and flowers that were aborted before seed provisioning became substantial. This strikingly large energy investment in floral parts is true for all species that display low seed or fruit sets (Stephenson 1981; Sutherland 1986; Ramirez & Berry 1997; Knight *et al.* 2005). A diversity of processes may be proximately responsible for low seedset, including pollen-limitation, poor pollen-tube growth, pollen incompatibility, selective abortion, and resource limitation (Ashman *et al.* 2004; Knight *et al.* 2005; Ruane, Rotzin & Congleton 2014). Many studies have investigated these effects, with different mechanisms likely responsible for low fruit set in different species, populations, and individuals. In contrast, fruit and seed abortion accounted for a small proportion of total accessory costs for most species (Table 1), with only four species investing more than 20% of their reproductive energy into tissues aborted post-pollination tissues, similar to that reported elsewhere (Lord & Westoby 2006, 2012; Rosenheim *et al.* 2014). This was expected, for aborting ovules before or just after pollination, instead of as larger fruits, reduces accessory costs, due to the lower resource investment up to the point of abortion Calviño (2014). Few seeds lost post-pollination also indicates limited pre-dispersal seed predation (Gómez 2008).

Success-associated costs, termed *seed costs* by us, are those required for the formation of a seed, including the seed itself plus pollen attraction tissues plus seed provisioning tissues (Figure 1, Table 1). For the two cone-bearing species, seed costs represented approximately half of total reproductive investment, while other species spent 3-42% of reproductive investment on seedcosts. For non-cone-bearing species this was lower than investment in failed tissues, but it was still a sizeable amount of energy that plants must spend for each seed produced. Between species variation in accessory cost components reflected differences in seed set and floral morphology across species. *Banksia ericifolia,* with small flowers, low seed set, and high provisioning costs spent only 0.4% of accessory costs on pollen-attraction tissues associated with successful ovules, while *Pimelea linifolia* with relatively larger flowers, smaller seeds, and higher seedset spent 65% of total accessory costs on pollen-attraction tissues associated with successful ovules. Species producing cones had two of the proportionally highest provisioning costs: *Banksia ericifolia* (61%) and *Petrophile puchella* (38% of total accessory costs). Due to *Conospermum ericifolium*’s stout fruiting stalks, it spent 29% of total accessory costs on seed provisioning costs. These results are broadly consistent with other studies recording how accessory costs shift across species within a community (Henery & Westoby 2001; Obeso 2004; Lord & Westoby 2006, 2012; Martinez, Garcia & Ramon Obeso 2007; Chen *et al.* 2010). In the following sections we explore whether the relative investment in different accessory cost pools shifts predictably with two species’ traits, seed size and seed set.

## Shifts in accessory costs with seed size and seed set across species

It is well established that seed size is an important plant functional trait and a species’ seed mass is the outcome of trade-offs with a collection of life history traits including longevity, plant height, and seed set (Westoby *et al.* 2002; Falster & Westoby 2005; Moles & Westoby 2006). Species with larger seeds produce fewer seeds, such that total investment in seeds per year increases nearly isometrically with seed size (Moles *et al.* 2004) (slope = 0.57 for species in this study, (r2=0.53, p =0.003), increasing to slope = 0.77 (r2=0.57 , p =0.003) if *Epacris microphylla* is excluded). Since direct investment in seed dry mass represents a modest component of total reproductive investment, shifts in the relative allocation of energy to seeds versus accessory tissues with seed size would be a potentially important trade-off across species. However, confirming the results of previous studies (Henery & Westoby 2001; Moles *et al.* 2003; Lord & Westoby 2006, 2012; Chen *et al.* 2010), accessory costs increased isometrically with seed size (Figure 4, Table 3). That is, the relative investment in seeds versus accessory costs did not shift with seed size and did not represent a variable that differentiates species from one another. Given the enormous diversity of floral forms and the known adaptive function of many floral parts (Harder & Barrett 2006; Harder & Johnson 2009) it is an excellent affirmation of theories on optimal energy allocation that the total reproductive investment was, relative to seed size, constant across species (Rosenheim *et al.* 2010; Mironchenko & Kozłowski 2014).

Dividing total accessory costs into the specific accessory tissue types outlined in Figure 1, allowed us to test for the existence of additional trade-offs, as the division into these smaller energy pools reflects further branch-points in plant energy allocation. For instance, relative investment in pre- versus post-pollination accessory cost components predicts where a plant lies along the pollen-limitation to resource-limitation spectrum (Haig & Westoby 1988; Burd 2008; Rosenheim *et al.* 2014, 2016) and we hypothesized this would also be correlated with seed size and seedset. To determine if the three accessory tissue pools identified in Figure 1 shifted across species, we regressed each against seed size. The results show that larger-seeded species invested disproportionately in packaging and dispersal (Table 3, Figure 5), in agreement with Lord & Westoby’s results (2006, 2012, but see Chen *et al.* 2010). This is expected, since larger seeds tend to have biotic dispersal agents, and animal-dispersed species allocate a greater proportion of their reproductive energy to packaging and dispersal materials (Hughes *et al.* 1994; Moles *et al.* 2005; Eriksson 2008).

Previous studies (Lord & Westoby 2006, 2012) defined a single pool of pre-pollination tissues and found that total pre-pollination costs scale isometrically with seed size. We instead divided these tissues into those associated with seeds that matured (required pre-pollination tissues, a component of total seedcosts) versus the costs of failed buds and flowers (failed pre-pollination tissues). This allowed us to show that the cost of failed buds and flowers scaled isometrically with seed size, while required pre-pollination costs scaled with a slope significantly <1 (Table 3, Figure 5). Since all but one species had failed pre-pollination costs that were at least twice as large as required pre-pollination costs and for some species one hundred times as large as required pre-pollination costs, failed pre-pollen costs would dominate the “all pre-pollen costs pool” and the regression between all pre-pollen costs and seed size, concealing the relationship between required pre-pollination costs and seed size. The cost of failed fruits and seeds also scaled isometrically with seed size (Table 3), but represents a much more modest energy expenditure (Table 1).

This collection of results emphasizes that there is a trade-off between investment in required pre-pollination tissues and packaging and dispersal tissues, similar to that proposed by Haig & Westoby (1988), and this trade-off correlates with seed size. (Note that, we are explicitly comparing investment just in seedcosts, while the Haig & Westoby model considers all pre-pollination and seed provisioning tissues.) The less-than-isometric slope between required pre-pollination tissues and seed size indicates that, pre-pollination tissues are cheaper for larger-seeded species to construct. In contrast, the greater-than-isometric slope between provisioning costs and seed size indicates that packaging and dispersal tissues require proportionally greater reproductive investment in larger-seeded species (Table 2). Moreover, in both previous studies (Moles & Westoby 2006) and the current data set, species with larger seed size are observed to have lower seed set, adding yet another dimension to the pre-pollination vs. post-pollination provisioning gradient.

Overall, larger-seeded species are parental optimists, producing abundant cheap flowers (and ovules). Post-pollination costs are relatively greater for these species, so on average only a few of the many ovules produced will progress to become mature seeds, leading to a low seedset (Figure 5a). Since producing additional flowers induces a relatively low cost, these species are selected to produce sufficient flowers to minimize pollen limitation through an over-production of ovules (Schreiber *et al.* 2015; Rosenheim *et al.* 2015). However, these species have only sufficient resources to provision a modest number of seeds and will abort all but a few ovules, pollinated or un-pollinated. Indeed, as shown in Figure 5c, the large-seeded species that make cheap flowers, make disproportionately many flowers: the slope of the regression between bud count (scaled to plant size) and seed size is shallower than -1, while the regression between seed count and seed size is indistinguishable from -1. Their seed production, indicating their fitness, scales isometrically to their seed size, while flower production, an intermediate step, does not. The final investment in seeds then matches theoretical expectations – species either make many small seeds or proportionally fewer heavier ones (Moles & Westoby 2006).

Haig & Westoby’s (1988) model has been extended to model how the trade-off curves shifts in stochastic environments and with different levels of individual variation in pollen receipt (Burd 2008; Burd *et al.* 2009; Rosenheim *et al.* 2014, 2015). Among their conclusions, species in stochastic environments will generally over invest in the tissue type that is relatively cheaper. For the parental optimists, with less costly pre-pollination materials, this means that an overabundance of ovules is produced – and usually aborted – but there are additional ovules that can be matured when sufficient resources are available (Andrade *et al.* 2005; Sadras 2007; Burd *et al.* 2009; Schreiber *et al.* 2015; Rosenheim *et al.* 2015). For these species, an additional benefit of having excess ovules pollinated is that they can be more selective in terms of pollen receipt (Zimmerman & Pyke 1988). Not only is an increase in per-flower ovule number a mechanism to reduce total accessory costs (Haig & Westoby 1988), but an oversupply of ovules slightly lessens overall pollen limitation, by increasing the proportion of pollen grains that are used (Rosenheim *et al.* 2015, but see Burd 2008). This effect is slightly larger than the decrease in the proportion of ovules fertilized due to the increase in ovule number. Although the authors of these models have reached different conclusions regarding the frequency of pollen-limitation in natural ecosystems, they have both established that species with greater pre-pollination costs produce relatively fewer more expensive flowers and have a greater probability of being pollen-limited while species with greater post-pollination costs will display the opposite set of trait values.

In summary, the correlations observed in our study indicate that seed size, bud production, and the magnitude of specific accessory cost components are coordinated across species. Understanding how plants allocate their pool of available reproductive energy to different accessory tissues and the seeds themselves is very relevant to understanding a plant’s energy allocation. Accessory costs constitute an enormous proportion of plant reproductive investment and plants must evolve to ensure these resources are invested to maximize their fitness.

## Shifts in accessory costs with plant size and age

A second motivation for this study was to determine if accessory costs shifted with plant age, size or reproductive investment (RE). The theoretical literature suggests that for plants to increase their allocation to reproduction (versus growth) as they grow and age, plants must realize some compounding benefit (Myers & Doyle 1983; Sibly *et al.* 1985; Kozlowski 1992). Increasing mortality with age and concurrent decreases in future reproductive value, is one mechanism that can increase RA in older plants. Decreasing accessory costs, and hence more efficient seed production, with increasing reproductive allocation is another obvious compounding benefit. If, for instance, accessory costs declined with RE, plants should be selected to have fewer, larger reproductive episodes (Kelly 1994; Kelly & Sork 2002) or delay reproduction until they are larger and can invest more energy in reproduction (Wenk & Falster 2015). However, although all of these species increased their relative allocation to reproduction (versus growth) with age and size (Wenk & Falster, unpublished data), not a single one of the 14 species showed a significant decrease in accessory costs with plant size or RE (while *Epacris microphylla* showed an increase) and only one species showed a significant decrease with age (versus two species that increased accessory costs with age) (Table 6).

The consistent lack of shift in per seed accessory costs (or seedset, data not shown) with RE (or bud count, data not shown) is notable. There is a large literature on expected and observed trends in pollination and seedset with the size of the floral display, with quite disparate patterns, but we had not anticipated a flat relationship for 13 of 14 species. In some studies, larger inflorescences or simply more flowers on a plant increased seedset by disproportionately attracting pollinators (Ruane *et al.* 2014). However, larger floral displays may alternatively lead to the greater deposition of self-pollen, decreasing seedset in self-incompatible species (Ruane *et al.* 2014). Herbivory can also disproportionately reduce seedset of individuals in specific age, size, or investment classes. In one study, increased reproductive investment reduced seedset, because higher bud counts increased the activity of a specialist insect herbivore (Miller, Tyre & Louda 2006; Miller, Tenhumberg & Louda 2008). Overall, experimental results variously indicate positive, negative, and flat relationships between flower numbers and seedset (de Jong *et al.* 1992; Goulson *et al.* 1998; Ashman *et al.* 2004; Knight *et al.* 2005; Ruane *et al.* 2014 and references therein), with pollen-limitation presented as the factor most likely limiting seedset (but see Knight *et al.* 2006; Rosenheim *et al.* 2014).

In conclusion, for many species, the sample sizes of the current data set are large and for most species we sampled across their entire age range, such that if a shift in accessory costs (or accessory cost components) existed it should have been detected in this data. We conclude that for many of these species the shifts in accessory costs were very small or non-existent with respect to size, age or RE. For these species, the observed shifts in RE or relative reproductive investment (RA) with size and age did not occur because the relative cost of producing a seed changed along the axis. Instead, other factors, such as mortality or compounding benefits of investing in growth at certain ages were driving shifts in RE and RA with size and age (reviewed in Wenk & Falster 2015).

* *Probably don’t include: The increased accessory costs LEES and PUTU display with age are likely due to the significant decrease in seedset displayed by older individuals of these species. In contrast, the significant age-related shifts shown by BOLE are not related to significant shifts with seedset.*

## Estimating reproductive investment

Realistic estimates of reproductive investment and accessory costs are essential to parameterize plant functional growth models. These models require estimates of the proportion of photosynthetic energy that is allocated to growth versus reproduction (###refs). Demographic models will also need to know how many seeds are produced for a given reproductive investment (###refs). The first measure, reproductive allocation, is a focus of our other research efforts, and is not touched upon here. As described above, this data set shows that across species total accessory costs scaled isometrically with seed size, indicating that total reproductive investment, *on a species level*, could be broadly estimated by knowing seed size (r2 = 0.52 (*p = 0.0035*), increasing to r2 = 0.67 (*p = 0.0007*) if *Epacris microphylla* is omitted). Total plant weight was equally strongly correlated with seed size *on a species level* (r2 = 0.57, *p = 0.0017*). These relationships simply show that larger-seeded species were bigger and therefore had more energy going to reproduction. However, to estimate reproductive investment for individual plants in a population, with different sizes and ages, information other than seed size is required.

The detailed measurements made for this study are not however practical for many research projects and pointing researchers to the best rapidly-obtainable estimates of total reproductive investment would be beneficial to many. We asked if knowing the investment in one of the components of total reproductive investment, such as investment in seeds, fruit or flowers provided a good estimate of total reproductive investment (Table 7). The strongest correlate was investment in failed tissues (r2=0.94 8; Table 4), which primarily represented investment in aborted flowers and buds (Table 1). Total seed investment (seed count \* seed mass) was a much poorer predictor of reproductive investment with r2=0.52, while the correlation against total fruit investment had an r2 of just 0.36 (Table 7). Unfortunately, determining how many buds, flowers, fruit, and seeds are aborted is not a “quick measure”, requiring repeat visits to the field and tedious accounting. We therefore created an artificial, composite measure: “total bud count \* average flower weight at the time of pollination” and determined that this was equally strongly correlated with reproductive investment as total failed tissues (r2=0.93). For species where most of their buds are visible at a single point in time doing a single bud count and determining flower weight for the species is a manageable prospect. Bud count on its own is not comparable across species, since the relative energy expenditure per flower is very different across species (see previous section). Within individual species, the strength of the correlation between total reproductive investment and seed investment varied from r2=0.30-0.90, with one species not even displaying a significant correlation across individuals (Table 6). In contrast, the correlation between total reproductive investment and our composite measure, was highly significant for all species with r2=0.52-1.000, again indicating it was the superior estimate of total reproductive investment. These results conversely demonstrate that if your research question requires seed investment or seed count as an output, estimates of total reproductive investment will not accurately predict seed production.

An alternative was a “top-down” approach, asking how well measures of plant size were correlated with reproductive investment or seed investment (Table 7b). The simplest of metrics to measure, plant basal diameter had the best predictive power, with an r2=0.66 for the relationship with total reproductive investment across all individuals, although either total plant weight or leaf area are nearly as accurate alternatives (Appendix). For all of these measures, correlations using all data points mask that, for some species, the relationship between plant basal diameter and reproductive investment is very strong (r2>0.60 for 4 species) while for others there is only a loose correlation (r2<0.30 for 5 species). The three measures of total plant size were much more poorly correlated with investment in seeds, either across all data points (r2=0.33-0.40 for the three measures) or within species. Indeed, only for 5 species was there even a significant correlation between plant diameter and seed investment. The message is again simple: If your research question requires an estimate of total reproductive investment, plant diameter plus knowing whether an individual is reproductively mature does account for a fair fraction of the variation. If seed production is the sought-after variable, actual seed counts must be made. The stronger relationship between plant size and total reproductive investment, versus seed investment, supports the findings in previous datasets (Henery & Westoby 2001)###ref.

The explanation for the poor correlation between seed investment and either plant size or total reproductive investment is clear: most of these species have relatively low seedset (Table 1) and moreover, seed set is quite variable across individuals in the population and across species (Table 6). Therefore, although the number of initiated buds is well-predicted by plant size (for most species) and is in turn tightly correlated with total reproductive investment (for all species), the unpredictability of seedset and overall low seedset means that investment in seeds, at the individual level, cannot be predicted by any easy-to-measure metrics. Many stochastic processes, from pollinator activity to pollen compatibility to resource availability lie between bud production and seed production (Herrera *et al.* 1998; Wesselingh 2007; Gómez 2008). These processes lead to both individual and inter-annual variation in seed production (Copland & Whelan 1989; Mitchell 1997; Herrera *et al.* 1998).

The strong correlation between total leaf area (or plant size or plant diameter) and total reproductive investment within most species, suggests that total reproductive investment is controlled by resource availability. Producing flowers, whether aborted or successful, represents the vast majority of plant energy investment (Table 1) and the number of flowers produced is strongly correlated with leaf area for all species. Although seedset is notably variable across individuals, limiting the correlation between flower production and seed production in our study, flower production is the reproductive trait with a significant selection gradient in the largest number of studies (Harder & Johnson 2009 and references therein), indicating its importance to plant fitness. Previous studies have also shown that resource availability controls flower production (Campbell & Halama 1993). Moreover, the correlation between reproductive investment (or bud count) and leaf area was strongest for two of the three species that produce a single flower (or inflorescence) bud at each leaf node on the previous year’s growth (*Hakea teretifolia* and *Epacris microphylla*). The third species, *Persoonia lanceolata* showed a quite weak correlation between leaf area and bud production, possibly because its leaves are large, few in number, and long-lived. Two additional species that had quite strong correlations, *Boronia ledifolia* and *Leucopogon esquamatus*, produce flowers at each leaf node, but *Boronia* produces between 1-5 flowers per node and *Leucopogon* 1-2 flowers per node, weakening the correlation.

For the six largest-seeded species and one-smaller seeded species, investment in seeds did not increase significantly with increasing leaf area, while there was a strong positive correlation for most smaller-seeded species. This is likely because large-seeded species show more individual variation in seed investment, simply because each seed represents a larger proportion of total seed investment.

## Considerations

To reach meaningful conclusions about the strength of trade-offs between total accessory costs or particular accessory cost pools and seed size, seed set or any other trait, accurate measurements of total reproductive investment is essential. Our accounting scheme is very good, but of course imperfect. The largest source of error is that we have not measured nectar production, despite knowing that several of the species (in particular *Banksia ericifolia*, *Hakea teretifolia* andboth *Grevillea* species produce abundant nectar) (###). Very rough back of the envelope calculations, based on studies of closely related species in nearby communities, indicate nectar production increases total reproductive investment by ~20% for *Grevillea speciosa*, 10% for *Hakea teretifolia*, and well under 5% for the other two species (###). These seemingly large energy expenditures, segue to our next consideration: Is dry weight the best measure of energy expenditure, especially in a community growing on soils known to be very low in P (###)? Previous studies indicate that nutrient concentrations may better estimate energy allocation choices (Reekie & Bazzaz 1987b; Ashman 1994; Rosenheim *et al.* 2014), but also that all currencies yield similar results. It is however, possible that in a P-limited community, it is less “costly” to produce copious quantities of nectar, for carbon is not limiting. This is a direction for future investigations. A final consideration, is how to choose which tissues to include as “reproductive tissues”, since some green reproductive tissues are known to photosynthesize (Cohen 1976; Reekie & Bazzaz 1987a; Wesselingh 2007). Since the net photosynthetic benefit of green reproductive tissues was unknown in this study and likely varied enormously across species, tissues and time, we adopted the parsimonious approach of considering all plant parts produced solely for the benefit of reproduction as components of reproductive investment.

The coastal heath community in eastern Australia has been well studied, both as a focal point for data collection on trait ecology and because of a general interest in the family Proteaceae, a dominant in this and many nearby communities. Indeed, 7 of the 14 species in this study are in Proteaceae, a family known to have particularly low fruit set (Hermanutz *et al.* 1998) (###) and to produce large woody fruits designed to allow seeds to withstand the frequent fires and then germinate following fire. Five species of *Gevillea* studied in communities nearby had fruit set between 1.5-9.6% (Hermanutz *et al.* 1998), similar to the seedset of the two species growing at our study site (Table 1). Notably, *Grevillea* species tend not to be self-incompatible, with the low fruit set attributed to pollen limitation and flower and fruit predation. *Banksia ericifolia*, *Hakea teretifolia*, and *Petrophile pulchella* all have fire-resistant fruits, and *Banksia* and *Hakea* have the largest seeds and greatest packaging and dispersal investment among the species in this study. Also of interest, although none of the species included in the study are explicitly masting species, the two cone-producing species, *Banksia* and *Petrophile*, do not form seeds each year (pers. obs.). This is shown at the population level by the large number of reproductively mature individuals that do not produce any seeds – or sometimes even any buds – in a given year. As has been shown in other species of *Banksia* (Copland & Whelan 1989), the inter-annual variability in seed production for these species may be due to resource limitation in the year following seed production.

## Conclusions

[ideally Discussions would end with some sort of tidy wind-up, referring back to the single most important conclusion]

[It's good that in this draft you've tried to be comprehensive about thoughts and reading. But generally my feeling is that a submitted version should be shorter, and cut down to the most positive points that you really want to make]

NOTES….

* Is it possible that seed set decreases for some species at oldest sites, because fewer individuals of a species remain in the area – greater pollen limitation? (Haig &Westoby 1991 propose that species with lower accessory costs do better when rare than do species with higher accessory costs; termed lower cost of rarity); PHPH and PUTU certainly become rarer, but weak correlation for PUTU, none for PHPH with age

References not in manuscript

* Recent papers, especially in the horticultural literature, have shown a variety of mechanisms whereby hormonal changes will limit flower production or additional fruit maturation. For instance, abscisic acid production was reduced in the year following a big fruit yield and in trees where fruits are removed (Shalom *et al.* 2014).
* Several recent reviews have identified a diverse pollinator community as increasing seedset (Albrecht *et al.* 2012; Garibaldi *et al.* 2015).
* Zhang et al. (Zhang *et al.* 2015) observed that bumble bees are superior pollinators of peach trees, relative to honey bees because …
* Németh MB, Smith-Huerta NL (2006) Effects of pollen load size and maternal plant on pollen performance and seedling vigor in Clarkia unguiculata (Onagraceae). International Journal of Botany 2: 83–
* (Saa & Brown 2014)- reduced photosynthesis in fruit-bearing branches
* (Thompson & Stewart 1981) – call RA measure of greatest importance as well
* (Primack 1987)
* (Goulson *et al.* 1998; Harder *et al.* 2004),
* (Ackerman 2000) – book chapter worth reading on pollination
* (Cruden 2000) – book chapter on pollen grain – ovule ratios for different pollination syndromes
* Mehlman 1993,Obeso 2004 – within species, larger seeds, more seed/fruit = lower disp costs
* (Lázaro, Jakobsson & Totland 2013) Good references for seedset on page 888, including: “At the within-species level, several studies have shown that the total number of visits to a plant increases with its flower number (Eckhart 1991; Makino et al. 2007), but in a decelerating manner (Robertson and Macnair 1995; Ohashi and Yahara 2002; Mitchell et al. 2004). One reason for such a pattern may be that insects attempt to avoid revisiting previously visited, and thus less rewarding, flowers (Dreisig 1995). As a consequence, visitation rate and seed set per flower may be independent of (Robertson and Macnair 1995; Goulson et al. 1998; Mitchell et al. 2004), or even decrease with, flower number (Klinkhamer and de Jong 1990; Grindeland et al. 2005).”
* pollen limitation is higher in species with larger floral displays (Lázaro *et al.* 2013).
* (Gómez 2008) – article showing that different factors drive selection at different stages in seed (and seedling) development. In particular, pollinators drive # flowers and # seeds initiated, resource controls # seeds initiated and pre-disp seed predors = # final seeds
  + Pollinator preference for large flowers is common to many other plant species (Conner et al. 1996b; Lloyd and Barrett 1996; Shykoff et al. 1997
* (Knight *et al.* 2005)
  + Larger flowered species have less pollen limitation – Momose 2004
* (Harder & Johnson 2009): “This review has revealed somewhat contrasting views of floral and inflorescence adaptation. On one hand, the survey of phenotypic selection studies indicates that selection on individual traits acts sporadically within populations and inconsistently among populations. On the other hand, experimental studies of pollination function usually demonstrate the adaptive nature of floral and inflorescence traits in prevailing pollination environments and phylogenetic studies reveal patterns consistent with a key role for adaptation of pollination systems in floral diversification.”
* (Burd *et al.* 2009) more ovules per flowers in species with greater variation in pollen receipt
* We now show that the opposite is the case, namely, that whole-plant pollen receipt (the parameter used by our model) is more predictable than pollen receipt by individual flowers and that by deploying larger numbers of flowers, plants lessen their uncertainty in pollen receipt. (Rosenheim 2016)
* . High RE due to masting would increase seedset through seed predator satiation and reduced pollen limitation in wind-pollinated species, thereby reducing accessory costs (Kelly 1994; Kelly & Sork 2002). While “masting” implies synchronous reproduction peaks across a population of plants, higher RE could also reduce accessory costs at the individual level, if, for instance, a larger floral display reduced pollen-limitation by an insect, avian, or mammalian pollinator.

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