

Five decades of misunderstanding in the social Hymenoptera: a review and meta-analysis of Michener's paradox

Robert L. Jeanne^{1†*} , Kevin J. Loope^{2†*} , Andrew M. Bouwma³, Erik V. Nordheim⁴ and Michael L. Smith⁵

¹*Department of Entomology, University of Wisconsin, 1630 Linden Drive, Madison, WI, 53706, U.S.A.*

²*Department of Fish and Wildlife Conservation, Virginia Polytechnic Institute and State University (Virginia Tech), Cheatham Hall, 310 W. Campus Drive, Blacksburg, VA, 24060, U.S.A.*

³*Department of Integrative Biology, Oregon State University, Cordley Hall, 3029, 2701 SW Campus Way, Corvallis, OR, 97331, U.S.A.*

⁴*Department of Statistics, University of Wisconsin, 1300 University Avenue, Madison, WI, 53706, U.S.A.*

⁵*Department of Biological Sciences, Auburn University, Auburn, AL, 36849, U.S.A.*

ABSTRACT

In a much-cited 1964 paper entitled “Reproductive efficiency in relation to colony size in hymenopterous societies,” Charles Michener investigated the correlation between a colony's size and its reproductive efficiency – the ability of its adult females to produce reproductives, measured as *per-capita* output. Based on his analysis of published data from destructively sampled colonies in 18 species, he reported that in most of these species efficiency decreased with increasing colony size. His conclusion that efficiency is higher in smaller groups has since gained widespread acceptance. But it created a seeming paradox: how can natural selection maintain social behaviour when a female apparently enjoys her highest *per-capita* output by working alone? Here we treat Michener's pattern as a hypothesis and perform the first large-scale test of its prediction across the eusocial Hymenoptera. Because data on actual output of reproductives were not available for most species, Michener used various proxies, such as nest size, numbers of brood, or amounts of stored food. We show that for each of Michener's data sets the reported decline in *per-capita* productivity can be explained by factors other than decreasing efficiency, calling into question his conclusion that declining efficiency is the cause of the pattern. The most prominent cause of bias is the failure of the proxy to capture all forms of output in which the colony invests during the course of its ontogeny. Other biasing factors include seasonal effects and a variety of methodological flaws in the data sets he used. We then summarize the results of 215 data sets drawn from post-1964 studies of 80 species in 33 genera that better control for these factors. Of these, 163 data sets are included in two meta-analyses that statistically synthesize the available data on the relationship between colony size and efficiency, accounting for variable sample sizes and non-independence among the data sets. The overall effect, and those for most taxonomic subgroups, indicates no loss of efficiency with increasing colony size. Two exceptional taxa, the halictid bees and independent-founding paper wasps, show negative trends consistent with the Michener hypothesis in some species. We conclude that in most species, particularly those with large colony sizes, the hypothesis of decreasing efficiency with increasing colony size is not supported. Finally, we explore potential mechanisms through which the level of efficiency can decrease, be maintained, or even increase, as colonies increase in size.

Key words: Hymenoptera, ergonomic efficiency, division of labour, colony size, colony development, social evolution

* Authors for correspondence (Tel.: +1 608 271 9481; E-mail: rjjeanne@wisc.edu); (E-mail: kjloope@gmail.com)

† Authors contributed equally.

CONTENTS

I. Introduction	1560
II. The meaning of efficiency	1562
III. Measuring ergonomic efficiency	1563
(1) Measuring ergonomic efficiency at the colony level: sampling methods, proxies, and pitfalls	1563
(2) Measuring ergonomic efficiency at the individual level	1566
IV. Sources of error in MICHENER'S estimates of ergonomic efficiency	1569
(1) Intrinsic effects: colony ontogeny	1569
(2) Extrinsic effects: season	1570
(3) Methodological flaws	1571
(a) Combining several species for analysis	1571
(b) Failure to include all input and/or output	1571
(i) Stored food	1571
(ii) Collection error	1571
(iii) Lack of temporal congruence of input and output	1571
(c) Inappropriate experimental design	1572
V. Systematized review of post-MICHENER studies	1572
(1) Methods	1573
(a) Review of the literature	1573
(b) Statistical analysis	1574
(2) Bees	1583
(a) Colletid and halictid bees	1583
(b) Ceratinine and allodapine bees	1583
(c) <i>Bombus</i>	1589
(d) <i>Apis</i>	1593
(3) Wasps	1594
(a) Vespine wasps	1594
(b) Independent-founding wasps	1594
(c) Swarm-founding wasps	1595
(4) Ants	1596
(5) Overall summary of review results	1596
VI. Meta-analysis of post-MICHENER studies	1596
(1) Meta-analysis methods	1597
(a) Data collection	1597
(b) Inclusion criteria	1597
(c) Multiple outputs	1597
(d) Effect sizes	1597
(e) Moderator variables	1598
(f) Phylogeny	1598
(g) Meta-analysis models	1598
(2) Meta-analysis results	1599
VII. Mechanisms	1599
(1) Task-performance gains	1600
(2) Task-integration gains	1602
VIII. Conclusions	1604
IX. Acknowledgements	1605
X. References	1606
XI. Supporting information	1610

I. INTRODUCTION

In an influential paper entitled “Reproductive efficiency in relation to colony size in hymenopterous societies”, Charles D. Michener (1964) examined the relationship between a colony's size and its *per-capita* output. His stated aims were “(i) to show that behavioural mechanisms exist which cause efficiency to vary in relation to colony size and (ii) to explain

certain aspects of the origin and evolution of colonies and of the non-reproductive worker caste” (Michener, 1964, p. 317). Although Michael V. Brian, working with ants, was among the first to investigate the relationship between colony size and efficiency (Brian, 1953, 1956a,b), Michener was the first to review the Hymenoptera literature on how efficiency scales with colony size within species. Using published data on several groups of social and semisocial Hymenoptera,

Michener plotted colony output – typically some measure of the amount of brood in the nest upon collection – as a function of colony size – usually measured as the number of adult females in the nest. Not surprisingly, in all 18 species of ants, bees, and wasps he examined, total colony output rose with colony size (Fig. 1A). But when colony output was divided by the number of females in the colony to yield output *per capita*, which Michener referred to as *reproductive efficiency*, the resulting measure decreased with increasing colony size (Fig. 1B) in all but two species. Michener concluded that this indicated “the existence (sic) of social patterns causing higher efficiency per female the smaller the group” (Michener, 1964, p. 334). This created a seeming paradox: how can natural selection favour and maintain social behaviour when a female apparently enjoys her highest *per-capita* output by working alone?

Over the more than five decades since its publication, Michener's paper has been cited hundreds of times, for the most part uncritically, as evidence that efficiency decreases with increasing colony size (e.g. Brian, 1965; Tschinkel, 1988, 1993; Hölldobler

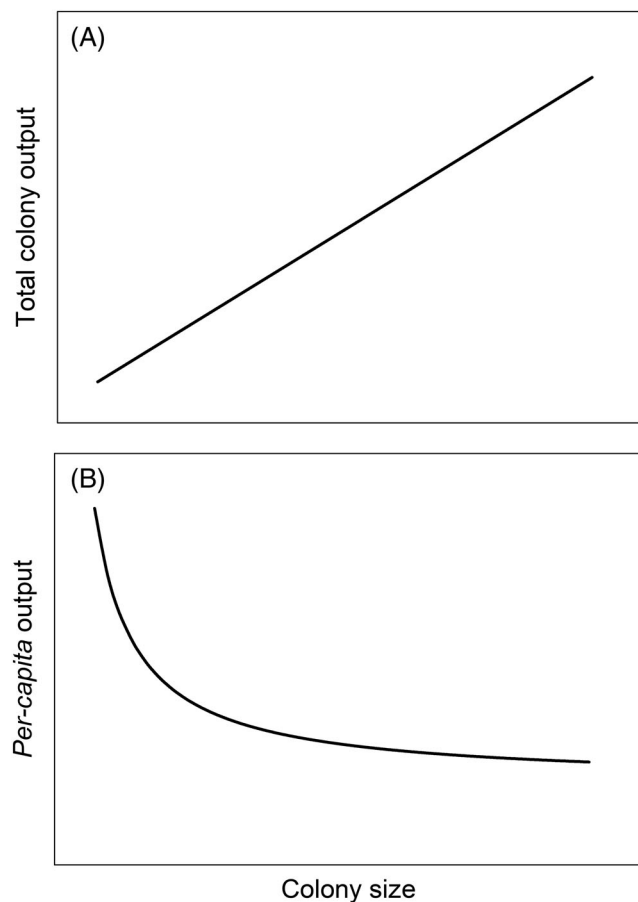


Fig. 1. Colony productivity and the Michener pattern. Outputs (*y*-axis) reported by Michener were various measures of brood in the nest. While total colony output increases with colony size (A), *per-capita* output decreases with colony size (B). This is the crux of Michener's paradox: it suggests that an individual would do better to reproduce on her own or in a small group than to join a large group.

& Wilson, 1990; Wenzel & Pickering, 1991; Foster, 2004; Powers & Lehmann, 2016; Stroeymeyt, Joye & Keller, 2017). This relationship has been referred to variously as the *reproductivity effect* of colony size (Wilson, 1971), a *rule* (Michener, 1974), an *anti-social factor* (Wilson, 1975), a *general feature* of social insect colonies (Bourke & Franks, 1995, p. 332), a *general pattern* (Karsai & Wenzel, 1998), a *key, recurring trend* (Reeve & Hölldobler, 2007), and as *Michener's paradox* (Wenzel & Pickering, 1991). Thus, Michener's conclusion has gained widespread acceptance and has taken on the status of conventional wisdom (Starr, 2006). Although some authors have noted that the pattern is not universal and have cited exceptions in taxa they work with (e.g. Schwarz, Bull & Hogendoorn, 1998; Shreeves & Field, 2002; Smith, Wcislo & O'Donnell, 2007; Modlmeier & Foitzik, 2011), there has been no thorough review of the matter. Our goal is to provide that here.

There is no disputing the general pattern Michener reported: *per-capita* productivity, as measured in the studies he cited, does indeed decrease in larger colonies in most of the published data sets he analysed. What is open to question is whether the measures he used actually evaluated *efficiency*, the focus of his paper, in any meaningful sense of the term. Michener used *efficiency* and *reproductive efficiency* interchangeably, defining them as the ability of the adult females of the colony to produce reproductives of the next generation. Because most of the studies he reviewed did not measure output directly in terms of numbers of sexuals produced, he used the number of immature individuals in a colony as an index of that ability (Michener, 1964). Although Michener's aim was to evaluate the effect of a colony's size on its efficiency, for most of the data sets he analysed, the indices, or proxies, he used for measures of output and/or input were influenced by a variety of factors other than colony size alone. These include the stage of colony development (ontogeny), seasonal effects, and the use of experimental procedures not designed to measure efficiency. Michener openly acknowledged these shortcomings but did not take them fully into account to temper the conclusions he drew from his analyses. For these reasons, the appropriate response to his proposition that efficiency decreases as colony size increases would have been to treat the pattern as a hypothesis to be tested, but the social-insect research community has largely failed to recognize this and take up the challenge.

For several reasons, the question Michener raised is an important one. First, because of its pivotal effect on the evolution and maintenance of eusociality itself, colony efficiency plays an essential role in efforts to model the process (Fu, Kocher & Nowak, 2015; Field & Toyozumi, 2020). Second, it is a key component of life-history strategies (Poitrineau, Mitesser & Poethke, 2009). Third, efficiency is a colony-level phenotype through which natural selection acts not only on colony size, but on such traits as division of labour, task partitioning, and mechanisms of colony integration *via* cues and signals (Goldsby *et al.*, 2012). Finally, it is central to the fascinating but little-addressed question of how selective forces interact to determine species-typical colony size among the social insects (Michener, 1964; Wenzel & Pickering, 1991; Queller, 1996; Clouse, 2001; Kramer, Scharf & Foitzik, 2014).

Our objective in this review is to treat Michener's pattern as a hypothesis and to take preliminary steps towards testing it by disentangling the assortment of causes behind the declines in *per-capita* output he reported. We state the hypothesis as follows: *an ontogenetic increase in colony size has a negative effect on colony efficiency*. We view a significant negative effect as supporting the hypothesis and a significant positive effect as evidence against it. A neutral effect may indicate no negative effect and thus constitute evidence against the hypothesis, provided the study has sufficient power to detect a significant effect.

Partly as a result of its lack of clarity in interpreting Michener's paper, the scientific community has barely begun to investigate the cause–effect relationships between colony size and efficiency, the question Michener originally sought to answer. Does larger colony size within a species enable greater efficiency through worker specialization and enhanced integration? Or, conversely, is efficiency reduced because workers in larger groups are more likely to get in one another's way, or work at cross purposes, as Michener contemplated? Theoretical arguments can be made for both sides (Clark & Fewell, 2014).

We begin in Section II with a close look at the meaning of the term *efficiency*, arguing that for a social insect colony it must be defined as some measure of total output (e.g. sexuals produced) in relation to some measure of total input (e.g. workers), measured over some unit of time. Ideally, measures of both output and input should be in terms of biomass or energy.

Section III provides a closer examination of how to measure efficiency and the pitfalls of using proxies.

In Section IV we scrutinize the data sets Michener used, teasing apart the various causes of the reduced *per-capita* output he reported. Specifically, we ask whether each of the studies he cited provides evidence that efficiency decreases with increasing colony size. We show that while Michener's intent was to investigate the effect of colony size on efficiency, the data sets he analysed used proxies for input and output that did not fully measure colony efficiency. We conclude that most of his examples do not support his conclusion, and that virtually all can be explained by the effects of colony ontogeny, season, or experimental procedures that were not designed to measure efficiency. Despite these shortcomings, Michener performed a valuable service by calling attention to the issue of efficiency and by providing an initial analysis.

Section V is a review of evidence accumulated from the 1960s to the present, focusing on studies that control for the several factors that confounded Michener's analyses. We carry out a systematized review of the literature on colony size *versus* efficiency relationships across the bees, wasps, and ants. We conclude that across most taxa, a majority of data sets show a neutral or even a positive effect of colony size on efficiency, although the independent-founding paper wasps and halictid bees have substantially more negative than positive effects, suggesting possible Michener effects in some of these species.

Section VI presents a meta-analysis of colony size and efficiency relationships across the studies reviewed in Section V.

This lends statistical support to the conclusion that, with the exception of select families, social insect species do not systematically exhibit declining efficiency with increasing colony size. Clarifying the issues in this way calls into question whether the so-called paradox exists for those species and points to the need for further exploration of the notable variation among species.

Finally, in Section VII we consider potential mechanisms behind changes in efficiency across colony size.

II. THE MEANING OF EFFICIENCY

Michener's aim was to examine the relationship between colony size and the “ability of adult females (queens and workers) of the colony to produce reproductives of the next generation” (Michener, 1964, p. 337), or what he called *reproductive efficiency*. Efficiency is generally understood in terms of ergonomics, the ability of workers, human or otherwise, to execute tasks with a minimum expenditure of time and effort. It is clear that what Michener wanted to examine was efficiency in this commonly understood sense. We maintain that the concept of efficiency is useful only in this sense of relating to time and energy budgets of colony members and of the colony as a whole (Oster & Wilson, 1978; Anderson & Ratnieks, 1999). At the colony level, it is the ratio of some measure of total output produced to some measure of total input, per unit time. Defining efficiency in this way recognizes that how efficiently workers organize and execute tasks is a discrete social trait, a component of fitness that is subject to natural selection (Modlmeier & Foitzik, 2011; Scharf *et al.*, 2012b), and therefore is worthy of study in its own right. The ultimate question Michener was interested in, and the one we address in this review, is how the efficiency with which colonies of a given species organize and carry out social tasks is affected by colony size.

Ideally, input and output should be measured in units of energy, but this is rarely achievable, especially over the entire colony cycle. Another close approximator of colony efficiency is total biomass of sexuals produced (output) divided by the biomass of workers produced over the entire cycle (input), but this is also rarely practicable. Instead, various proxies have been used as more accessible surrogates for input and/or output. Most of the data sets Michener analysed used more easily measured stand-ins for input and output. These will be discussed in Sections III and IV. For now, the important point to make is that if the proxies that are used do not accurately represent a colony's total input and total output, they will not yield accurate measures of its efficiency, and must be interpreted carefully.

We define the terms we use in this review as follows:

Productivity (= *reproductivity*) (*P*). The products (output) of colony effort, including immatures being reared, sexuals produced, food stored, nest structure built, etc., measured as number, biomass, or energy content.

Michener used the two terms interchangeably (Michener, 1964, 1974). We prefer 'productivity' because it is shorter, more general, and because *reproductivity* carries the connotation of production of offspring only (Tierney, Schwarz & Adams, 1997). In Michener's analyses various measures of colony growth were used as proxies for the output of sexuals. Often this was measured as the standing crop of brood in the nest when it was collected.

Colony size (S). The size of the colony, typically measured as the number or biomass of females in the colony at the time of collection.

Per-capita productivity (PCP). Productivity divided by some measure of input, such as the number of colony members (females), that produced the output. Thus, in many studies $PCP = P/S$.

Efficiency (E). All forms of colony output divided by all forms of colony input, measured over a standardized time period. It is ideally measured in units of energy, in which case it is a unitless ratio. In practice, the number of females in the colony is often used both as a proxy for input and as a measure of colony size, *S*. If PCP includes all forms of input and output it is a valid measure of colony efficiency, *E* (Fig. 2).

We maintain that only if declining *per-capita* productivity can be attributed to decreasing efficiency as defined above can there be a paradox. If we are careful to take account of all forms of a colony's output – its investment in the nest, production of workers, collection and storage of food, defence against enemies, homeostatic maintenance of conditions conducive to survival and growth, in addition to its production of sexuals – then we have accurately measured the colony's efficiency (Fig. 2). If we then find that total *per-capita* output decreases with colony size, we encounter the paradox.

Finally, it is important to recognize the role of colony survivorship and to distinguish it from colony efficiency. If the purpose is to calculate *overall fitness* – or mean *expected* output of newly initiated colonies in a population – then the risk of failure must be factored in. It is often the case that smaller colonies survive at lower rates than do larger ones (Gibo & Metcalf, 1978; Litte, 1981; Bull & Schwarz, 1996; Tschinkel, 2017). This differential success has been invoked to resolve the 'paradox' (Michener, 1964; Hölldobler & Wilson, 1990; Karsai & Wenzel, 1998) by recognizing that larger colonies may be maintained in a species' population because they have a higher expectation of producing reproductives, even if their colony efficiency may be lower (Fig. 3, circles). By contrast, because efficiency is an intrinsic property of a colony it can be measured only in successful (i.e. living) colonies (Fig. 3, × symbols). We return to this issue in the next section.

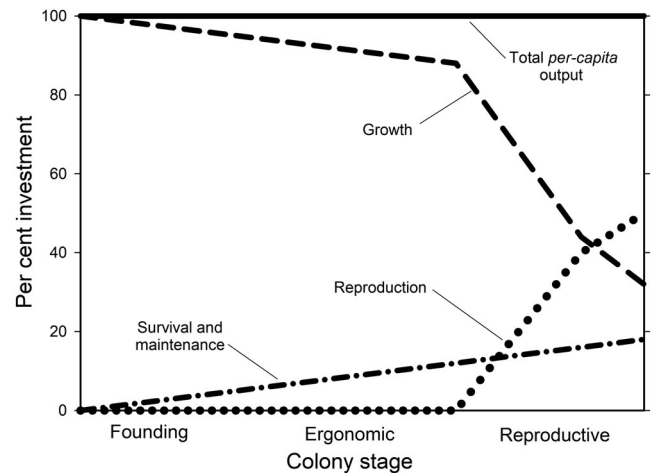


Fig. 2. Changing allocation of *per-capita* investment among major forms of output during the colony cycle. Total investment (100%) is shown by the solid line at the top; it captures all forms of colony output (productivity) and represents the colony's efficiency (*E*). The three components of output – growth, survival and maintenance, and reproduction – sum to this total 100% at every stage. Michener's commonly used proxy for *per-capita* output is represented by the growth line (dashed). Early in development, growth in worker numbers is the major form of output, but as the colony develops it invests increasingly in survival/maintenance (dot-dashed line), and finally in reproduction (dotted line). These redirections of effort come at the expense of growth. Therefore, growth, the proxy metric for efficiency in most of Michener's analyses (typically measured in terms of numbers of cells or immatures in the nest at collection) gives a good approximation of efficiency early in the colony cycle but becomes increasingly inaccurate as the colony develops. A plot of *per-capita* productivity (PCP) based on this proxy will decline with increasing colony size during development, just as in Michener's plots, but that plot will not accurately depict the colony's efficiency across all developmental stages or its ability to produce reproductives.

Assessing the interaction of colony size and fitness was not Michener's purpose (all his data sets comprised successful colonies only) and is not our purpose here. The aim of this review is to focus on the intrinsic trait of ergonomic efficiency and to investigate its response to colony size by stripping away confounding factors that can bias measures of efficiency.

III. MEASURING ERGONOMIC EFFICIENCY

Ergonomic efficiency can be measured at two levels, the colony and the individual. The vast majority of studies, and all of Michener's analyses, deal with colony-level efficiency, so we consider it first.

(1) Measuring ergonomic efficiency at the colony level: sampling methods, proxies, and pitfalls

A reliable measure of the efficiency of a colony can be calculated as total sexuals produced (output) divided by total

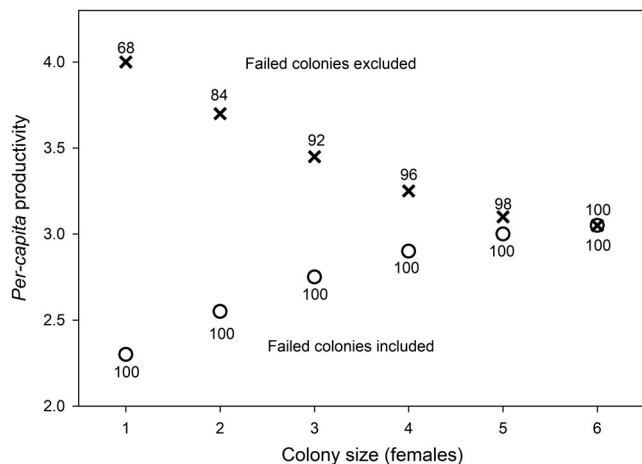


Fig. 3. The effect of including (O) versus excluding (×) failed colonies on calculations of *per-capita* productivity (PCP) as a function of colony size. Sample size = 100 for each colony size. Rate of colony failure decreases with increasing colony size. Numbers indicate number of colonies included in each calculation of PCP; for each colony size the difference between colony numbers included gives the number of failed colonies. The upper plot is a measure of colony efficiency, while the lower plot is a measure of overall relative fitness.

workers required to produce them (input). A study that comes close to this is Morgan Webb's analysis of productivity in bumble bees (*Bombus* spp.) (Webb, 1961). In what can be called a full-cycle longitudinal study (FCLS), Webb monitored housed field colonies continuously, starting with the early post-emergence stage, and individually marked all emerging worker and reproductive offspring. Thus, his data provided a direct measure of near-total input (total numbers of workers across the lifetime of the colony) and total output (numbers of sexuals produced) over the major part of the post-emergence stage of the colony cycle. Because all of the colony's output (including food collected, stored, and utilized during the season) was captured in the final product, the gynes and drones, the ratio of sexuals produced per worker can be taken as a close approximation of the colony's ergonomic efficiency. Webb's results for *Bombus pensylvanicus* (De Geer) (= *americanorum*) showed a significant positive effect of worker number on *per-capita* output of sexuals (Fig. 4), and his data for *B. griseocollis* (De Geer) and *B. auricomus* (Robertson) showed the same pattern (see Section V.2c below). (Sample sizes for two additional species were too small to analyse.) The only explanation for this pattern is that colony efficiency increases with colony size. A refinement would be to measure input in terms of worker-days instead of just worker numbers. A second improvement would be to measure output in terms of biomass or energy rather than numbers, to account for the fact that *Bombus* gynes and drones differ in biomass and are substantially larger and more costly to produce than are workers (Del Castillo & Fairbairn, 2012) (see Section III.2).

Such a direct approach is not only labour-intensive but is feasible only for species whose adults and brood can be

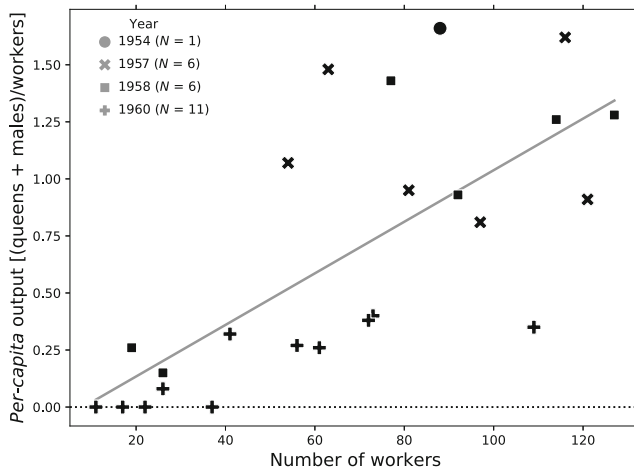


Fig. 4. *Per-capita* productivity of *Bombus pensylvanicus* (= *americanorum*) colonies, based on total numbers of workers (W) and sexuals produced over the entire season. Seven colonies parasitized by *B. (Psithyrus) variabilis* (Cresson) are omitted because output of the host species was compromised. The four colonies shown with values of $y = 0$ did not die, but simply failed to produce males (M) or gynes (Q). Regression equation: $(M + Q)/W = -0.092 + 0.0113 W$, $r^2 = 0.52$, $N = 24$. Slope is significantly different from 0 at $P < 0.001$. Both slope and y -intercept are significantly affected by year. Data from Webb (1961, table 26).

accessed, marked, and censused daily (e.g. independent-founding wasps) or can be artificially housed for observation (e.g. twig-nesting bees, bumble bees, honey bees, some wasps and ants). Data in this form were rare in the literature in 1964 and remain rare to this day.

Most of the data sets Michener analysed came from single-point-in-time censuses of destructively sampled (DS) colonies, so direct measures of total sexual output were not possible. Instead, Michener made a compelling argument for the use of proxies for the production of sexuals: "...there are excellent reasons to believe that the ability of a colony to produce workers is positively correlated with its ability to produce sexual forms" (Michener, 1964, p. 320). He cited Webb's results in support of the correlation. Thus, Michener's analyses typically used numbers of immatures or provisioned cells in the collected nests as proxies for output and the number of females (queens and workers) collected with the nests as proxies for input.

Michener recognized that using proxies for the efficiency of production of reproductives requires that certain assumptions be met. Foremost among these is that colony stage be held constant across the samples: "[o]ntogenetic studies of colony populations confuse results due primarily to colony size itself with those due to the seasonal and age factors" (Michener, 1964, p. 320). By "colony size itself" he meant variation in the sizes of colonies *at the same stage of development*, not to size increases during development. Even if colony stage (and other biasing factors – see Section IV) are strictly controlled, colony size within a local population of a species can still vary. For example, the sizes of founding swarms of

honey bees and epiponine wasps vary widely. Colonies of haplometrotically founding species (e.g. bumble bees, independent-founding wasps) at identical post-founding ages or stages may also vary widely in size, reflecting differential success in converting resources into offspring and in avoiding attrition of workers due to predation (Bourke & Franks, 1995).

Although the data sets Michener analysed contain a number of shortcomings (see Section IV), the issue of lack of control for ontogenetic changes in a colony's output is the most common, so we give it special attention here. To illustrate the bias imposed by the use of proxies in this context, consider the following scenario. Imagine a eusocial species living in an aseasonal tropical environment. Assume for simplicity that it lacks morphological castes and does not store food. Emulating the methods behind many of the data sets Michener analysed in his review, we destructively sample a large number of colonies of all sizes over the course of several days. As Michener did for many of his analyses, we measure colony size as the number of females, our proxy for input, and measure productivity as the number of brood in the nest, the proxy for output of reproductives. We calculate *per-capita* productivity (PCP) by dividing the number of brood (output) by the number of females (input). Regressing PCP on colony size for our collected samples, we see that the regression slope is negative; that is, larger colonies have lower values of PCP than smaller ones. Can we conclude that the decline means that workers in larger colonies are somehow less ergonomically efficient than in smaller ones? Clearly not, because our sample may include colonies at all stages of development. Suppose that the average worker brings in enough food either to rear two immatures or to maintain two adults. For a small colony in the founding or early ergonomic stage (no adult reproductives yet produced), virtually all of the workers' effort is going into colony growth, so our proxy for output – number or biomass of brood – provides a reasonable accounting of all productivity (see Fig. 2). Suppose that when this colony is collected it has 50 workers and 100 brood; according to our proxy, PCP is $100/50 = 2.0$ brood/worker. Now suppose another colony in our sample is in the reproductive stage and is larger. Our census reveals 200 workers, 350 brood, and 50 adult gynes and males. These adult sexuals must be fed but contribute no work (input). Our calculation of PCP for this colony is $350/200 = 1.75$, less than that of the smaller colony. Recognizing that maintaining each sexual means that one less brood can be reared, we have an explanation for the reduced number of immatures. In terms of the rate at which they bring in food, the workers in the large colony are just as efficient as in the smaller one, but our proxy has not captured the new form of output – the maintenance of the adult sexuals – and for this reason our measure of PCP does not accurately measure colony efficiency. The ontogenetic shift from rearing workers to rearing sexuals is an essential, adaptive part of the colony's life-history strategy. It will not in and of itself lead to selection for smaller colonies, and therefore the decline in PCP recorded for the larger colony is hardly paradoxical.

A further potential biasing factor in this scenario is that the gynes may not be distinguishable from workers (e.g. in some

sweat bees and wasps), and thus get counted on the input side of the equation. If, in the above example, there are 25 gynes in the larger colony but they get counted as workers, our calculation of PCP becomes $350/225 = 1.55$. Therefore, because our results are based only on output of immatures – our proxy for productivity – they tell us nothing useful about either ergonomic efficiency or *per-capita* production of sexuals in relation to colony size. The decline in PCP is an artifact of our choice of a proxy.

As an alternative scenario, suppose instead that we meet all the assumptions behind using proxies for input and output. Let us say we limit our sample to colonies that are just at the end of the founding stage and are about to produce their first adult (worker) offspring. Thus, we know that all the adults in each sample count as input, and everything else – the nest and the brood – counts as output. Now we have a measure of colony efficiency, a valid estimate of how efficient each colony will be at producing sexuals. Suppose our plot of PCP on colony size for this sample shows a decline. Now we have a paradox. If unopposed, natural selection should shift colony size downward, to sizes where *per-capita* output is greater. Why this does not happen is a valid question, and the answer will often be that larger colonies have a greater probability of surviving to reproduce (see Section II). Even without investing relatively more in defensive structures (e.g. a hardened nest) or specialized workers (e.g. soldiers), having more workers is alone enough to elevate the colony's effectiveness in defending against predators, in buffering the effect of abiotic challenges, and in avoiding colony extinction by random attrition of adults. That is, if the greater expectation of survival of larger colonies exceeds the cost of their reduced efficiency, larger colonies will be maintained by natural selection because they enjoy greater fitness than do smaller colonies.

In addition to FCLS and DS, two additional sampling methods have been used in the literature. One is non-destructive sampling (NDS) at one or more points in time. This technique is sometimes used for ants, where collection of entire colonies can be difficult. Proxies are used for input and output, but these are measured non-destructively. For example, the size of nest mounds or mark-and-recapture techniques may be used to estimate colony size (see for example Cole & Wiernasz, 2000).

The second method is two-point longitudinal sampling (TPLS). The colony is non-destructively sampled at stage A of development and again (often destructively) at point B after the elapse of a fixed amount of time, and the production gains are calculated. The proxy for input is usually the number of workers at point A or B, or some calculated middle value; proxy for output is typically the net gain in standing crop of brood over the interval. This approach is feasible for species whose colony members are accessible to observation or can be non-destructively censused at point A, for example at founding.

With both FCLS and TPLS it is often the case that some of the colonies included in the cohort at point A do not survive to point B. Rather than assigning a value of 0 to the productivity of non-surviving colonies, they must be removed from

the cohort. As argued in the previous section, the reason is that ergonomic efficiency is a trait intrinsic to the colony and therefore cannot be measured in colonies that fail. (As an analogy, suppose that in a study of the rate of mass gain in older humans we follow a cohort of 50-year-olds for 25 years. The calculation of the cohort's mean mass at age 75 clearly should not include values of 0 for individuals who did not survive to that age.) Excluding failed colonies assumes that their failure is not related to the unobserved rate of *per-capita* productivity. Whether this assumption is met for any species is not known (Gibo, 1978; Strassmann, Queller & Hughes, 1988; Shakarad & Gadagkar, 1995), but is unlikely to be the case. If failure is more common among less-efficient colonies, or among small colonies, excluding them will raise the left-hand end of the regression of *per-capita* output on colony size (Fig. 3), moving the curve in the direction of support for the hypothesis, thus raising the bar for rejecting it. By contrast, if colonies fail for reasons unrelated to level of ergonomic efficiency and colony size – for example, loss of the nest to a large predator – excluding failed colonies will have no effect on the shape of the regression curve of *per-capita* output on colony size.

Two additional biasing factors should be mentioned. One has to do with the widespread use of counts of brood or provisioned cells as proxies for output. The data sets Michener analysed used counts, as do the majority of the more recent studies we analyse below. The most accurate measure of output would be in the form of energy invested by the colony to produce it. A reasonable approximation of this, at least for brood, would be the total biomass of the standing crop in the nest, although energy stored in brood may not correlate closely with biomass. In monomorphic species, for example, the biomass of workers and gynes may be identical, but if gynes contain a higher proportion of lipid, their energy content may be greater (Boomsma & Isaaks, 1985). Counts can be misleading representations of energy/biomass in three ways. First, as pointed out above, for species with size differences among castes – either workers *versus* sexuals (e.g. vespines, *Bombus*, *Apis*) or among workers (some ant species) – counts will not capture variation among colonies in the proportions of the castes among the brood. Second, there is evidence for some species that the size of offspring varies with the number of founding females (Goodisman & Ross, 1996; Clouse, 2001). Third, even for monomorphic species, if two colonies have the same total number of immatures, but differ in the proportions of eggs, larvae, and pupae, only biomass will accurately capture the difference in productivity between the two, given the large differences in biomass among brood stages. A good example of misleading brood-count data comes from Spradbery's (1971) study of the wasp *Vespula vulgaris*. Plotting total brood number *versus* worker number suggests declining efficiency in larger colonies (figure 10 in Spradbery, 1971). In our reanalysis using pupal biomass data (calculated from pupal counts and corrected for mean caste biomasses reported in Archer, 2012), efficiency shows no decrease and is essentially linear with colony size

(Fig. 5A; see Section V.3a and online Supporting Information, Table S1, for details). In conducting our meta-analysis (see below), we found 28 data sets from 18 species reporting both measures of brood production output – counts and biomass. We compared these 28 pairs of efficiency estimates by regressing $\log(\text{total output})$ on $\log(\text{colony size})$ (see Section V.1b for more on this statistical approach for estimating efficiency), and plotting the difference in slope between each pair of measures (Fig. 5B). In most cases (26 of 28), the use of brood mass yields a higher slope, closer to 1.0 (no effect of size on efficiency). This bias in effect size – the difference between slopes – is significant (paired *t*-test: $t_{27} = 3.99$, $P < 0.001$). Clearly, using brood counts generates a bias in favour of the Michener paradox pattern.

The second biasing factor is time. Ideally, efficiency should be measured as a rate, for example as biomass/per worker/day (Clouse, 2001). There is evidence for some social wasps that broods develop faster in larger founding groups (Litte, 1977b; Clouse, 2001; Howard & Jeanne, 2004; Ito & Itioka, 2008). If, as is common in studies of social wasps, the point at which output is measured is just prior to the eclosion of the first offspring, larger colonies will reach that point in fewer days than smaller colonies. Thus, efficiency measured as biomass or numbers of brood when the chosen stage of development is reached will underestimate the efficiency of larger colonies, whereas calculating *per-capita* productivity as a rate will more accurately reflect their greater investment. The conversion to a rate can readily be made in studies that measure output over a fixed period of time rather than to a stage of development (e.g. Jeanne & Nordheim, 1996; Bouwma, Nordheim & Jeanne, 2006). An associated potential bias introduced by using colony stage as a target point comes on the input side. Again, using swarm-founding wasps as an example, the size of the founding swarm decreases during the pre-emergence stage, largely due to mortality during foraging, at daily rates independent of swarm size (Bouwma *et al.*, 2003a,b). Thus, because small colonies take longer to reach a particular stage of development, the adults collected with the nest at that point represent a smaller proportion of the founding swarm than for larger colonies. This reduces the denominator in the calculation of PCP, thus artificially raising the estimate of colony efficiency relative to large colonies.

In conclusion, the metric that best avoids most of the above pitfalls is biomass of brood produced per worker per day. Only a minority of studies we review use such a metric.

(2) Measuring ergonomic efficiency at the individual level

While a proper colony-level analysis reveals the effect of colony size on the colony's overall ergonomic efficiency, it tells us nothing about the causes behind the colony-level pattern. An increase or decrease in colony-level efficiency begs the question of the mechanisms behind the effect. Efficiency at the sub-colony level can be broken down into two components:

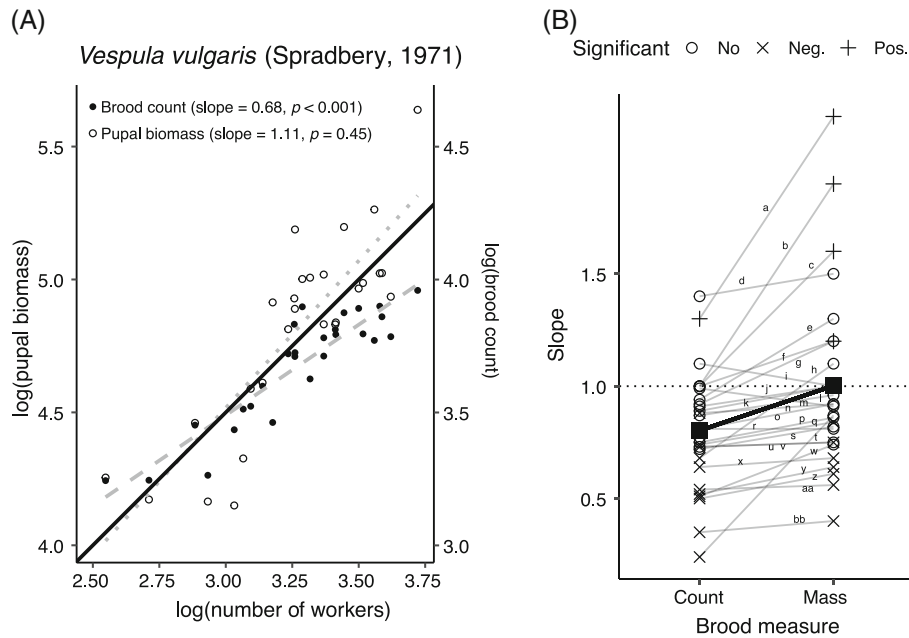


Fig. 5. The use of brood counts instead of brood masses creates a Michener pattern bias. (A) In one example, brood count data from Spradbery (1971) show the initial conclusion of a negative effect of colony size on efficiency in *Vespa vulgaris* (filled circles), with a slope (dashed line) significantly less than 1.0 (black line: neutral effect). However, when plotting pupal biomass data [pupal count data from the same study and biomass data from Archer (2012)], no negative effect is observed (open circles; dotted line). (B) A comparison of brood or cell counts versus brood masses as alternative proxies for measuring productivity. The symbols represent the slopes of the regressions of log(colony output) on log(colony size); lines connect the plot of count with the plot of mass for each of the 28 data sets. A slope of 1.0 indicates no effect of colony size on ergonomic efficiency. A + indicates a slope significantly greater than 1.0, while an × indicates a slope significantly less than 1.0. Filled squares are mean values for the groups. Data sets: a, *Exoneura nigrescens* (Nov) (Stevens et al., 2007); b, *E. nigrescens* (Dec) (Stevens et al., 2007); c, *Parachartergus fraternus* (Bouwma et al., 2006); d, *Bombus lucorum* (Müller & Schmid-Hempel, 1992); e, *Polybia occidentalis* (1982) (Jeanne & Nordheim, 1996); f, *Temnothorax crassispinus* (Regensburg) (Kramer et al., 2014); g, *T. crassispinus* (Abensberg) (Kramer et al., 2014); h, *Vespa vulgaris* (Spradbery, 1971); i, *Lasius sakagamii* (winter larvae) (Yamauchi et al., 1982); j, *Polybia occidentalis* (1998) (Bouwma et al., 2005); k, *Apis mellifera* (brood) (Lee & Winston, 1985); l, *T. nylanderi* (Sommerhausen West) (Kramer et al., 2014); m, *P. occidentalis* (1983) (Jeanne & Nordheim, 1996); n, *T. nylanderi* (Sommerhausen South) (Kramer et al., 2014); o, *P. occidentalis* (1999) (Bouwma et al., 2005); p, *T. americanus* (NY) (Kramer et al., 2014); q, *T. longispinosus* (NY) (Kramer et al., 2014); r, *Leptothorax acervorum* (Abensberg) (Kramer et al., 2014); s, *T. americanus* (WV) (Kramer et al., 2014); t, *V. germanica* (Spradbery, 1971); u, *T. longispinosus* (WV) (Kramer et al., 2014); v, *Myrmica punctiventris* (NY) (Kramer et al., 2014); w, *Polistes dominula* (May) (Turillazzi et al., 1982); x, *Leptothorax muscorum* (Kramer et al., 2014); y, *T. nylanderi* (Scharf et al., 2012a); z, *Bombus terricola* (Owen et al., 1980); aa, *E. nigrescens* (Sept) (Stevens et al., 2007); bb, *Polistes dominula* (April) (Turillazzi et al., 1982).

Task-performance efficiency is the efficiency with which individual workers carry out social tasks, measured, for example, in worker-minutes. Efficiency can increase when workers learn to perform a task faster and/or at lower cost by specializing on that task. A foraging bee that has discovered a nearby patch of flowers will collect more resource per hour by specializing on one species and learning how to handle its flowers than will a generalist forager that visits several species or that switches between collecting nectar and pollen (Heinrich, 1976; Oster & Wilson, 1978; Jeanne, 1986a; Raine & Chittka, 2007; Chittka & Muller, 2009).

Task-integration efficiency is the efficiency with which a group of interacting individuals carries out a

set of related tasks requiring cooperation among members of the group. Cooperation can be enhanced through the use of local information transmitted via cues and signals. Examples include efficiency gains achieved through recruitment of nestmates to resources (Oster & Wilson, 1978) and the partitioning of materials-handling tasks among differently specialized individuals (Jeanne, 1986a; Ratnieks & Anderson, 1999; Anderson, Franks & McShea, 2001).

Studies at the individual level require an approach not unlike that used to analyse human productivity in terms of person-hours required to complete a task. The colony's workers are marked for individual recognition, then timed as they engage in social tasks. One example of this method is a study of nest construction in the swarm-founding wasp *Polybia occidentalis* (Olivier) (Jeanne, 1986b).

Table 1. Summary of data analysed by Michener (1964)

Genus species N = sample size	Fig.	Data source	Output variable(s)	Input variable	Sampling type	Biasing factor not controlled for							Effect of colony size on <i>per-capita</i> output		
						Spp	Ont	Sea	Out	Tem	Col	Exp		Michener analysis	Our analysis
<i> Ruizanthea divaricata</i> (Vachal) (= <i>Pseudogapostemon divaricatus</i>) N = 9	NP	Michener & Lange (1958)	No. cells containing eggs, small larvae, or pollen masses	No. females in nest	DS				x	?	?	NA	(No effect)		
<i> Augochloropsis sparsilis</i> (Vachal) N = 38–77	1	Michener (1964)	No. cells with eggs, small larvae, or pollen masses, per female	No. females in nest	DS	x	x	x	x	x	?	NA	(Negative)		
<i> Lasiglossum imitatum</i> (Smith) N = 109	2	Michener (1964)	No. cells with eggs, small larvae, or pollen masses	No. females in nest	DS	x	x	x	x	x	?	NA	(Negative)		
<i> L. rhytidophorum</i> (Moure) N = 69	3	Michener (1964)	No. cells with eggs, small larvae, or pollen masses	No. females in nest	DS	x	x	x	x	x	?	NA	(Negative)		
<i> Bombus pennsylvanicus</i> (De Geer) (= <i>americanorum</i>) N = 24	NP	Webb (1961)	Count of all workers, males, and gynes produced	No. workers produced	FCLS							NA	(Positive)	Positive	
<i> Apis mellifera</i> (Linnaeus) N = ~66	10	Farrar (1931)	Sealed brood cells, first week of May	No. females in nest	NDS	x			x			NA	(Negative)		
<i> Apis mellifera</i> N = 51	11	Farrar (1931)	Sealed brood cells, June 23–Sept. 24	No. females in nest	NDS	x	x	x	x	x		NA	(Negative)		
<i> Polybia bistrigata</i> (Fabricius) + <i> P. bicyliarella</i> Richards N = 20	4	Richards & Richards (1951)	No. cells with eggs	No. females in nest	DS	x	x	x	x	x	x	NA	(Negative)	Negative	
11 species in 5 genera N = 49	5	Richards & Richards (1951)	No. cells with eggs	No. females in nest	DS	x	x	x	x	x	x	NA	(Negative)	No effect	
<i> Myrmica rubra</i> (Linnaeus) N = 12	6	Brian (1950)	No. larvae/worker in overwintered colonies	No. workers in nest	DS							NA		No effect	
<i> Myrmica rubra</i> N = 12	NP	Brian (1950)	Grams larvae/worker in overwintered colonies	No. workers in nest	DS							NA		No effect	
<i> Myrmica rubra</i> N = 7	7	Brian (1953)	No. larvae metamorphosing after 17 days	No. workers in nest	Laboratory groups of varying ratios of workers and brood							NA	x	No effect	
<i> Myrmica rubra</i> N = 7	8	Brian (1953)	Increase in mean larval mass after 11 days	No. workers in nest	Laboratory groups of varying ratios of workers and brood							NA	x	Negative	Negative

(Continues)

Table 1. (Cont.)

Genus species N = sample size	Fig.	Data source	Output variable(s)	Input variable	Sampling type	Biasing factor not controlled for				Effect of colony size on <i>per-capita</i> output			
						Spp	Ont	Sea	Out	Tem	Col	Exp	Michener analysis
<i>Myrmica rubra</i> N = 9	9	Brian (1953)	No. larvae surviving after 25 days	No. workers in nest	Laboratory groups of varying ratios of workers and brood					NA	x	Negative	Negative

Note: Each species is scored for the types of errors that Michener's analysis is likely subject to. **Genus species** = species analysed. **Fig.** = figure number in Michener (1964) (NP = not plotted by Michener). **Data source** = original source of the data; **Output variable(s)** = measured product. **Input variable** = measure of colony size. **Sampling type:** DS = destructive sampling; NDS = non-destructive sampling; FCLS = full-cycle longitudinal sampling. **Biasing factor not controlled for** = factors (other than ergonomic efficiency) that can lead to the Michener pattern of declining *per-capita* output. **Spp** = inclusion of more than one species; **Ont** = ontogenetic effects; **Sea** = failure to include all forms of output; **Tem** = lack of temporal congruence of input and output; **Col** = collection error; **Exp** = inappropriate experimental design. Cell entries: x = commits the error; = not enough information to determine; NA = not applicable. **Effect of colony size on *per-capita* output** = slope of regression of *per-capita* output on colony size [at $P = 0.05$: positive, negative, no effect (not different from zero)]; **Michener analysis** = Michener's conclusion about slope; parentheses = not based on a statistical test; **Our analysis** = result of our statistical test in absence of Michener's and where data were available to us.

Potential mechanisms enabling increases or decreases in colony efficiency will be explored in more detail in Section VII.

While Michener openly acknowledged the requirements that the use of proxies imposed, despite his best intentions most of the data sets he analysed failed to meet them. The proxies used in the studies he analysed typically captured only a subset of each colony's total output (Fig. 2). As we show in the next section, because uncaptured forms of output were often neither controlled for nor accounted for by his surrogate measures for output of sexuals, the measures of *per-capita* productivity he reported are not reliable indicators of the effects of colony size on colony efficiency, and in fact reveal little of value.

IV. SOURCES OF ERROR IN MICHENER'S ESTIMATES OF ERGONOMIC EFFICIENCY

Our intent here is to assess whether the declines in *per-capita* productivity that Michener reported actually provided valid evidence of reduced ergonomic efficiency in larger groups. We do so by exploring the possible causes of the decline in each of his case studies. As explained above, because most of the studies Michener analysed used proxies for input and/or output, there is the potential for factors other than efficiency to bias the results. If the declines can be attributed to investment by larger colonies in forms of output not measured by his proxies, we can be sceptical that they are due to declining efficiency. In virtually all the data sets Michener analysed, this and/or other potential biasing factors were not controlled for. To illustrate the effects of each type of bias, we give one or more examples from his data sets. The examples given do not exhaust the issues attending each of Michener's data sets. Full results are summarized in Table 1.

(1) Intrinsic effects: colony ontogeny

As noted above, as a colony develops it progresses through programmed changes in its allocation of resources among various forms of output (Fig. 2) (Oster & Wilson, 1978; Fewell & Harrison, 2016). *Per-capita* productivity, typically measured *via* proxies such as numbers or biomass of brood reared per female, will be high during the founding and early ergonomic stages of rapid colony growth, when the colony is small. In later stages, when the colony is larger, the same metric will typically yield lower values because it fails to capture the increasingly important additional forms of output, such as investment in defence, homeostasis, food storage, and the production and maintenance of adult reproductives. The resulting apparent decline in *per-capita* productivity therefore cannot be attributed to declining colony efficiency. If a limited proxy for output is to be used, then the stage of colony development must be held constant.

Michener's analysis of productivity in swarm-founding wasps (Epiponini) is one of several of his data sets that have

this problem. His figure 4, for example, plots data for 20 colonies of *Polybia bistriata* (Fabricius) and *P. bicyttarella* Richards collected over 2 months in Guyana (latitude 6° N) by Richards & Richards (1951). Because Guyana's climate is relatively aseasonal, their samples included colonies at all stages of development. Several of the larger colonies contained adult males, which must be fed, diverting resources away from growth. In addition, larger colonies may have been preparing to send out swarms and therefore may not have been producing brood at full capacity. These effects could well have led to the lower values of *per-capita* productivity seen among the larger colonies in Michener's analysis, but for reasons having nothing to do with declining efficiency.

Another example is Michener's analysis of the honey bee (*Apis mellifera* Linnaeus) (his figure 10). The data came from overwintered, managed colonies sampled in Massachusetts in May by Farrar (1931). Honey bee colonies are perennial, and in the spring their size, developmental stage, and condition will vary (Fig. 6). Colonies with more workers begin to invest in reproduction in spring, whereas smaller colonies will refrain from reproduction until later in the season (Smith *et al.*, 2014; Smith, Ostwald & Seeley, 2016). Michener's measure for colony output was the number of sealed brood cells, but Farrar reported that he decapitated drone brood at each census, so we know that some of the colonies were already investing in reproductive, which Michener's measure of colony output would not have included. Therefore, the most populous colonies would already have diverted resources to reproduction at the expense of producing more workers, whereas the smaller colonies would still be investing heavily in growth of the worker population (see Fig. 2). These differences could well be the main cause behind the declining *per-capita* productivity curve that Michener reported for these bees.

Michener's analysis of *Augochloropsis sparsilis* (Vachal), a semisocial halictid bee, used his own data from Curitiba, Paraná, Brazil (latitude 25° S), where colony cycles are seasonally synchronized. Nests were sampled over a period of more than 4 months, thereby spanning much of the growing season. It is likely that there was attrition in the numbers of founding females, the measure of colony size (input) (Michener & Lange, 1959; Packer, 1993), while the number of cells containing pollen or young brood (output) increased. These trends would yield higher values of *per-capita* productivity later in the season, when colonies were smaller. Any effects of colony size on efficiency were likely obscured by these ontogenetic effects. Michener's analysis of *Ruizantheda divaricata* (Vachal) [= *Pseudagapostemon divaricatus* (Vachal)] from the same locality, based on nests excavated during a narrower time frame (1 month), showed no effect of colony size on *per-capita* output (Michener, 1964).

(2) Extrinsic effects: season

In temperate climates, season entrains ontogeny for species with annual colony cycles, but in many tropical regions this constraint is relaxed, so that colonies at all stages of development occur throughout the year. Yet even modest seasonality may affect colony growth. Colonies founded in a less-benign period – the tropical dry season, for example – may experience less-abundant food resources and therefore grow more slowly than those initiated in the wet season. Thus, even if care is taken to control for colony ontogeny, season may influence measures of the effect of colony size on efficiency in these habitats. Michener's data on *Lasioglossum rhytidophorum* (Moure), also from subtropical Curitiba, were collected over a period of 6 months and may have been differentially affected by seasonal differences in rainfall and temperature.

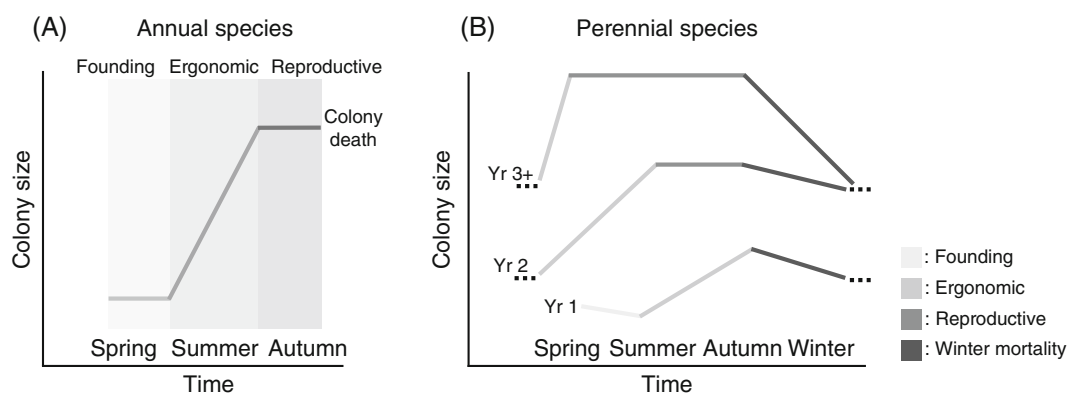


Fig. 6. Patterns of colony growth. Annual (A) and perennial (B) species show different patterns of growth depending on the time of year. In an annual species, the time of year correlates with the colony's stage of development, because all colonies are roughly on the same developmental trajectory (see also Fig. 2). In a perennial species, however, the age of the colony is as important as the time of year. A sample of colonies collected in early summer may include some that had recently been founded (Yr1), some that were investing heavily in growth/maintenance (Yr2) and some that were reproducing (Yr3+). Shading of lines denotes colony developmental stage: light grey = founding; medium grey = ergonomic; dark grey = reproduction; black = winter mortality. Black dotted lines connect surviving colonies from 1 year to the next.

(3) Methodological flaws

(a) Combining several species for analysis

Because species differ in their ontogenetic schedules and degrees of allocation of effort to growth, maintenance, and reproduction, combining species for an analysis of the effect of colony size *per se* on ergonomic efficiency is not a valid procedure. Although Michener acknowledged this, for his analysis of the Neotropical swarm-founding social wasps he combined species in order to obtain sample sizes large enough to analyse. Using data on swarm-founding wasp colonies collected in Guyana (Richards & Richards, 1951), the first of his two analyses (his figure 4) combined data for two similar species of *Polybia*, and his second (his figure 5) lumped data for 11 species in five genera. In both cases, *per-capita* productivity based on his proxy (number of eggs in the nest per female) decreased with increasing colony size. But because a species effect cannot be ruled out, the result cannot be accepted as supporting the hypothesis that efficiency decreases with colony size. Interspecific variation in colony efficiency is a topic worthy of investigation but is outside the scope of this review.

(b) Failure to include all input and/or output

Calculating colony efficiency based only on immatures, as Michener did, overlooks other potential forms of the colony's output, such as stored food and the nest structure itself (Bourke & Franks, 1995; Ostwald *et al.*, 2021). These can account for large fractions of a colony's effort and may vary significantly with season and colony size. If not considered or controlled for, these factors can confound efforts to estimate efficiency. We cite three examples: stored food, collection error, and lack of temporal congruence of input and output.

(i) *Stored food.* Basing colony efficiency on brood only, without accounting for energy devoted to collecting and storing food, underestimates efficiency. Indeed, larger colonies of *Apis mellifera* store more honey *per capita* than smaller ones. Colonies of 60000 bees stockpiled 1.54 times more honey per bee than did colonies of 15000 bees (Farrar, 1937; Moeller, 1961), the opposite of the Michener pattern. Unfortunately, converting all forms of colony output into a single common currency is not feasible for honey bees, as it would require too many assumptions to generate an accurate estimate of total *per-capita* output as a function of colony size.

(ii) *Collection error.* If colonies are collected during the day, as is often the case, foraging adults will be missed. The same is not true of measures of productivity, typically the numbers of brood or provisioned cells in the nest. This kind of error will reduce the denominator (input) in *per-capita* productivity calculations, causing an artificial increase in the ratio of output to input. Because the failure to collect even one adult from a small founding group can have a large effect, this kind of error may be greater for small colonies, and thus could contribute to the Michener pattern. Michener's analysis of the data of Richards & Richards (1951) on swarm-founding

wasps may be subject to this kind of error. Richards and Richards did not place a great deal of importance on capturing all the adults in a colony. Nests were often taken during the day, and in numerous cases at least some wasps, sometimes many, escaped as the nest was being taken.

(iii) *Lack of temporal congruence of input and output.* Destructive sampling (DS) provides data on the state of the colony at a single point in its development. This can lead to serious distortions in the calculation of PCP. Common measures of productivity such as numbers of brood or brood cells represent the investment by the adults over several weeks prior to collection, but the number of workers collected with the nest may be quite different from the number that produced those forms of output. During the ergonomic stage, because the worker population (measure of input) is growing, its size at collection may be higher than it was when the measured output was produced, yielding an artificially low estimate of PCP. During the founding stage of swarm-founding bees and wasps, the distortion becomes especially acute. In the wasps, for example, the number of brood – the measure of output – increases steadily, while the number of adult females – the measure of input – decreases by 50% in *Polybia* (Bouwma *et al.*, 2003a) or even up to 90% in *Apis* (Smith *et al.*, 2016), due to attrition without replacement. These changes will yield very low values of *per-capita* productivity early in the founding stage, when the colony is large, and high values towards the end of the founding stage, when the colony is smaller (Fig. 7). Thus, because the time periods represented by input and output are not congruent, the resulting values of *per-capita* productivity do not yield valid measures of ergonomic efficiency.

Michener's analysis of the swarm-founding wasps is a clear example (Michener, 1964, his figures 4 & 5). He used the number of eggs in the nest as a proxy for colony productivity, on the grounds that they represent recent output, i.e. the effort of females still present when the nest was collected. However, not only do eggs represent only a minuscule fraction of the output of workers, but the number of eggs varies widely during colony ontogeny, even during the founding stage. As modelled in Fig. 8, the ratio of eggs in the nest to females in the founding swarm skews strongly upward in founding-stage colonies, reaching its maximum when the worker population is at its minimum due to attrition. It then drops steeply during the subsequent ergonomic stage, when the number of workers is increasing. This is yet another reason why the results of Michener's swarm-founding wasp analysis cannot be taken as supporting the hypothesis.

Attaining full congruence requires certain conditions. Webb's (1961) *Bombus* study achieved it by including input (number of workers) and output (number of sexuals) over the entire colony cycle. TPLS that starts with founding is another viable option (e.g. Jeanne & Nordheim, 1996). If collected colonies are to provide reliable estimates of PCP, valid proxies for output must be chosen and the stage of colony development, season, and other biasing factors must be tightly controlled for across samples.

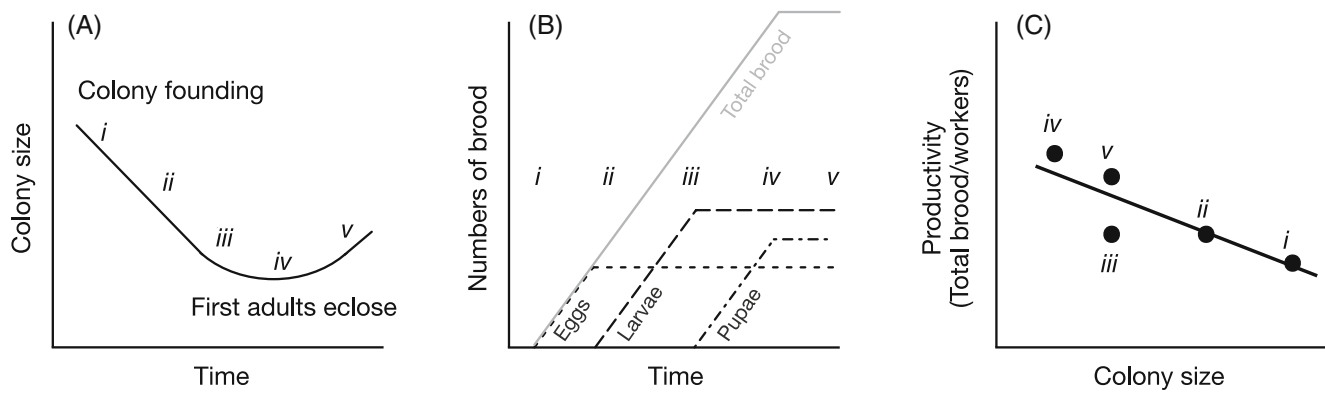


Fig. 7. Lack of congruence of input and output. Growth is depicted of a hypothetical swarm-founding colony that has established a new nest and begun to produce workers. (A) Colony size decreases due to worker mortality (points *i–iii*) until workers begin to eclose (*iv*), and colony size begins to increase (*v*). (B) The corresponding numbers of eggs, larvae, and pupae, assuming for simplicity constant rates of oviposition and constant development times. Each plateau represents the standing crop due to equal rates of brood entering and leaving that stage. Total brood (in grey), the sum of all forms of output (eggs + larvae + pupae) rises steadily until production plateaus. (C) This hypothetical colony is non-destructively sampled at times *i* to *v* to determine its *per-capita* productivity, that is, the number of brood the colony has reared divided by the number of workers in the colony at each point. This shows a negative relationship, like Michener's pattern, but the decline is simply due to the lack of congruence of input and output, and not to a difference in the efficiency of colonies of different sizes.

(c) *Inappropriate experimental design*

In his figures 7–9, Michener plotted the results of laboratory experiments on *Myrmica rubra* (Linnaeus) carried out by Brian (1953) to determine optimal ratios of larvae to workers. Variable numbers of workers (5–320) were provided with *ad libitum* food and a fixed number (50) of brood for them to rear. Productivity of the workers was measured in three ways: the number of larvae metamorphosing after 17 days, the increase in mean larval mass after 11 days, and the number of larvae surviving after 25 days. In each case, values of *per-capita* productivity were smallest for the largest numbers of workers. However, the conclusion that these results support the hypothesis would be incorrect. The *per-capita* output at higher worker numbers was very likely constrained by the fixed number of brood provided, and not by a decline in ergonomic efficiency, a point that Michener acknowledged (Michener, 1964, p. 336).

A better way experimentally to test the effect of group size on work-group efficiency is to vary group size while keeping the worker/larva ratio constant. Brian used this approach in a later study, in which he set up groups of 3, 6, 9, 12, 20, 40, 80, and 160 workers, each with an equivalent number of larvae (worker: larva ratio = 1), and maintained them on *ad libitum* food (Brian, 1956a). At the end of 10 days there was no significant effect of group size on mean larval mass gain. In a second experiment, a single group of 190 larvae and 30 workers produced a mean larval mass gain of 0.74 mg over a week, whereas 10 groups of 19 larvae and three workers each produced a mean mass gain of 1.23 mg in the same time period. At first glance this appears to support the hypothesis, but Brian pointed out that the apparent inefficiency of the larger group may have been due to the tendency of the workers to pile larvae, which limited workers' access to many of the larvae. He suggested that the artificial

nests he used may have encouraged this, while the low ceiling height in natural brood chambers would prevent the piling of brood. Again, one cannot conclude from this study that ergonomic efficiency declines with increasing group size. Laboratory experiments to measure ergonomic efficiency must be designed carefully.

We conclude that none of the 14 data sets analysed by Michener provide compelling evidence that colony efficiency decreases with increasing group size. As summarized in Table 1, in most of his analyses one or more factors unrelated to efficiency were not controlled for and could have caused the decrease. In cases where all factors apparently were controlled for, the slope of the regression of *per-capita* productivity on colony size did not differ significantly from zero. In fact, of all the data sets Michener included in his study, the *Bombus* results were the most compelling because total output of sexuals was measured directly over the entire reproductive stage of the colony cycle (Webb, 1961). Thus, it could be argued that Michener should have reached the opposite conclusion, that is, that workers in larger groups are more efficient, not less, compared to those in smaller groups.

While this analysis throws serious doubt on the hypothesis by identifying several factors other than ergonomic efficiency that could have caused the pattern, because there is no way to control for those factors *ex post facto*, the above analysis cannot disprove the hypothesis, but it does call it into question.

V. SYSTEMATIZED REVIEW OF POST-MICHENER STUDIES

Here we turn to studies published since Michener's analysis, plus some earlier work he did not include. Our primary aim

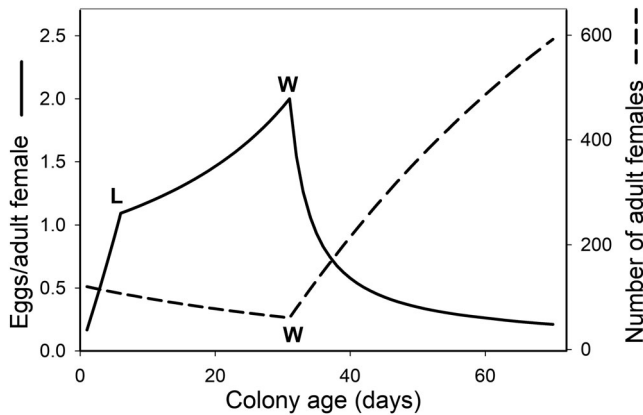


Fig. 8. Early-stage growth of a colony of swarm-founding wasps, with *per-capita* output based on eggs, per Michener (1964). Assumptions as in Fig. 6. Mortality of adults during the founding stage is 50% in the ~30 days it takes the colony to produce its first adult offspring (Bouwma *et al.*, 2003a). The number of eggs per adult female (solid line) starts low (few eggs, many females), then rises rapidly as oviposition continues and workers in the founding group (dashed line) die without replacement. As the oldest eggs begin to hatch into larvae (point L), the number of eggs in the nest becomes constant (rate of hatching equals rate of oviposition), but because adult mortality is ongoing (Bouwma *et al.*, 2003a) the number of eggs *per-capita* continues to rise, albeit more slowly than before, and reaches a peak when the adult population is at its lowest, just as new workers begin to eclose (point W). After that point the eggs-per-adult ratio decreases, because the adult population is now increasing while the number of eggs in the nest remains constant. Thus, the highest value of eggs/adult occurs at the end of the pre-emergence period, when the colony is smallest (point W). Relaxing the assumption of a constant colony-wide rate of oviposition by the queens to, say, a sigmoidal or declining function, has no qualitative effect on this ontogenetic pattern.

in this section is to summarize the available data sets relating colony size to ergonomic efficiency that control for the biasing factors reviewed above, and to gather data sets for a formal meta-analysis (Section VI). As Michener convincingly argued, if biasing variables such as season and stage of colony development are held constant, the values of PCP measured can reveal the effects of colony size on efficiency within the sample.

Our second purpose is to draw attention to the fact that the proxies used for input and output in these studies do matter. As we reasoned in Section II, proxies often incompletely and/or inaccurately sample input and/or output, and therefore cannot provide reliable measures of ergonomic efficiency. Some proxies for input and output can be valid metrics for assessing the effect of colony size on ergonomic efficiency, but they must be interpreted carefully. We illustrate this point by including in the tables below some studies that measure productivity using two or more proxies. Multiple metrics from the same study often show contradictory effects of colony size on *per-capita* output. Examples include Rangel & Seeley (2012) on *Apis mellifera*,

and Tschinkel (1999) and Kaspari & Byrne (1995) on ants. These reinforce the assertion made above that, even if biasing factors are controlled for, the choice of proxies used for input and output must be made and interpreted with caution. These cases also help to make our point that if all forms of input and output could be captured in a single, all-inclusive metric, the contradictory effects of different proxies for output would disappear.

(1) Methods

(a) Review of the literature

We conducted a systematized review (Grant & Booth, 2009; Oliveira *et al.*, 2021), using several approaches to locate studies that include data on colony productivity in a form that can be used to calculate ergonomic efficiency as a function of colony size.

We began by searching our personal digital reference libraries for relevant papers. Those in turn cited older studies. We supplemented those results with the following online searches. We used *Scopus* to find papers that cite Michener (1964). This search, completed on 15 April 2021, turned up 177 references. The same search conducted in *Google Scholar*, completed on 10 July 2021, found 277 references. Eighteen *Scopus* references were not duplicated in the *Google Scholar* search results; thus, the two searches yielded 295 references. We also performed *Web of Science* searches via the University of Wisconsin Libraries and selecting All Databases from the UW's collection (*Web of Science* Core Collection, Biological Abstracts, BIOSIS Citation Index, CABI: CAB Abstracts, Current Contents Connect, Data Citation Index, Inspec, KCI-Korean Journal Databases, MEDLINE, Russian Science Citation Index, SciELO Citation Index, Zoological Record). We used the search terms (bee OR ant OR wasp) AND social (entered in search box 1), AND "colony size*" OR "worker number*" (search box 2), AND (efficien* OR productiv*) OR per capita (search box 3). This was completed on 5 April, 2021 and returned 274 records, of which 46 were also included in the *Google Scholar* search results. Finally, *Web of Science* searches were performed for papers on selected major genera, using the search terms "(genus name) AND (productiv* OR efficien*)." These searches were completed May–July 2021.

The results of each online search were screened for data on *per-capita* productivity in two steps: first, working with the search results online, we eliminated from further consideration those judged from the title and abstract not to contain data on colony productivity as a function of size. Second, we downloaded PDFs of the remaining papers and examined the full text, again excluding those lacking relevant data. Both of these screening steps were carried out by one person (either R.L.J. or K.J.L.). The full text of each of the remaining papers was carefully examined by both of us, with a decision reached jointly on whether it met our criteria for inclusion in our tables (see below). In a few cases, additional references were located by screening potential candidates cited by the papers located and screened from the online searches.

We applied the following criteria for inclusion in our tabulations of studies on colony efficiency.

- (1) Data sets must exclude failed colonies. As explained above (Section III.1), we are focused strictly on the intrinsic ergonomic efficiency of a colony's production of reproductive offspring (or some correlated proxy thereof), independent of its probability of surviving to produce them. If it was not clear that results of a study did not include failed colonies, we excluded it. We make the plausible assumption that ergonomic efficiency plays little or no role in a colony's probability of failure. For allodapine bees, numerous studies reported PCP statistics that included colonies containing zero brood. We interpreted broodless colonies as failed, as ant predation is frequent and likely a major cause of broodlessness (Schwarz *et al.*, 1998; Zammit, Hogendoorn & Schwarz, 2008). We thus removed broodless colonies from data sets when possible and re-calculated summary statistics (see Section VI), and omitted studies for which we could not do so. As single-female colonies are much more likely to be broodless (Schwarz *et al.*, 1998), omitting them differentially boosts PCP in these smallest colonies and thus, if anything, biases results in favour of the Michener pattern. In the meta-analysis (see Section VI), we performed two versions, with and without broodless nests, to allow for the possibility that such nests are not purely the result of nest failure.
- (2) Data sets must control for the ontogenetic stage of colony development. In environments where colony initiations are limited to a few days at the beginning of the favourable season, we made this judgement based on the range of dates over which data were collected. If, in our judgement, the range of collection dates was too great, we excluded the data set. For studies of species in aseasonal environments, we judged whether adequate steps were taken to control for variation in stage of colony development. This meant, for example, that all relevant studies of stenogastrine wasps were excluded, as the observed colonies were likely in various stages of development (Field *et al.*, 2000; Shreeves & Field, 2002). Also, we restricted our analysis to studies that compared colonies that varied in size, rather than comparing between life stages of individual colonies that were monitored through time (e.g. Thomas, 2003; Clark & Fewell, 2014; Kramer *et al.*, 2015).
- (3) We excluded ant studies based on mound size, unless these measures were shown to be highly correlated with worker population (e.g. Cole & Wiernasz, 2000).
- (4) Sample size must be sufficient to enable statistical tests of the effect of colony size on output (minimum $N=7$). While this cut-off is arbitrary, the vast majority of data sets had sample sizes greater than 10, and thus we view the choice of threshold as unlikely to affect our results. We included studies in which the authors either

reported statistical tests on the effect of colony size on output or provided raw data enabling us to do so. We also included a few cases where the authors did not conduct statistical tests of the effect, but in which the sample size was adequate. We indicate these cases with a question mark in the Effect column in Tables 2–8.

- (5) We excluded studies involving experimental manipulations or laboratory settings that we deemed too invasive or unnatural to describe productivity effectively. We note that methods varied widely among the cited studies. In some cases, proxies for productivity were marginally valid. We took a somewhat liberal view, and included any study that, in our opinion, represented a reasonable representation of colony efficiency.

We retained 90 studies with a total of 215 data sets that met the above criteria (Tables 2–8).

Some studies report multiple output metrics for a given species. For example, multiple data sets may represent data for different years [e.g. *Halictus ligatus* Say (Litte, 1977a)], locations [e.g. *Lasioglossum lineare* (Schenck) (Knerer, 1983)], seasons [e.g. *Exoneura nigrescens* Friese (Stevens, Hogendoorn & Schwarz, 2007)], or stages of colony development [e.g. *Polistes dominula* (Christ) (Turillazzi *et al.*, 1982)]. We analysed these separately whenever possible, so colonies are compared to other colonies in the same location, season, and stage as far as possible. Other studies used two or more proxies for output for the same colonies. For such studies, we include results for two or more proxies to illustrate our point that some metrics are better proxies for colony efficiency than others. [e.g. *Apis mellifera* (Rangel & Seeley, 2012), *Pogonomyrmex badius* (Latreille) (Tschinkel, 1999)].

(b) Statistical analysis

The studies cited in this section use several methods of statistical analysis to assess the effect of colony size, S , on total colony productivity, P . The most common is to calculate productivity *per-capita*, P/S , and regress it on colony size, S , the independent variable. In the resulting regression equation ($P/S = mS + b$) if the slope, m , is not significantly different from 0, we conclude that colony size has no effect on *per-capita* productivity. If the slope is negative or positive and significantly different from 0, the effect of S is negative or positive, respectively.

A second method is directly to fit a regression of P on S . This approach can have the benefit of reducing non-homogeneity of variance that can occur in *per-capita* data. The shape of the curve, whether linear or curved, reflects the effect of colony size on productivity. One approach is to fit a model such as $P = b + m_1S + m_2S^2$ (e.g. see Kaspari & Byrne, 1995; Jeanne & Nordheim, 1996). If m_2 is not significantly different from 0, the last (non-linear) term drops out, leaving a linear relationship; i.e. colony size has no effect on *per-capita* productivity. If the non-linear coefficient m_2 is negative or positive and differs significantly from 0, we conclude

Table 2. Effect of colony size on *per-capita* productivity in Apoidea: Colletidae and Halictidae (sweat bees)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
A. Colletidae								
<i>Amphilaetus morosus</i> (Smith)	17	No. brood cells	No. females	No effect	Victoria, Australia	DS	Reused nests. 1 <i>zv.</i> 2 mated females per nest. Nov. 6, 1992 sampling.	Spessa <i>et al.</i> (2000)
<i>A. morosus</i>	11	No. brood cells	No. females	No effect	Victoria, Australia	DS	Reused nests. 1 <i>zv.</i> 2 mated females per nest. Nov. 25, 1992 sampling.	Spessa <i>et al.</i> (2000)
<i>A. morosus</i>	11	No. brood cells	No. females	No effect	Victoria, Australia	DS	Reused nests. 1 <i>zv.</i> 2 mated females per nest. Dec 20, 1992 sampling.	Spessa <i>et al.</i> (2000)
<i>A. morosus</i>	12	No. brood cells	No. females	No effect	Victoria, Australia	DS	Reused nests. 1 <i>zv.</i> 2 mated females per nest. Jan 8, 1992 sampling.	Spessa <i>et al.</i> (2000)
<i>A. morosus</i>	39	No. brood cells	No. females	No effect	Victoria, Australia	DS	Reused nests. 1 <i>zv.</i> 2 mated females per nest. Nov 20, 1993 sampling.	Spessa <i>et al.</i> (2000)
<i>A. morosus</i>	134	No. brood cells	No. females	No effect	Victoria, Australia	DS	Reused nests. 1 <i>zv.</i> 2 mated females per nest. End of brood production (Series 3).	Spessa <i>et al.</i> (2000)
<i>A. morosus</i>	134	No. surviving brood	No. females	No effect	Victoria, Australia	DS	Reused nests. 1 <i>zv.</i> 2 mated females per nest. End of brood production (Series 3).	Spessa <i>et al.</i> (2000)
B. Halictidae								
<i>Halictus ligatus</i> Say	20 (1974)	No. offspring of all stages	No. founding females	Negative?	New York, USA	DS	Spring nests. 1–3 foundresses. No statistics performed.	Litte (1977a)
<i>H. ligatus</i>	11 (1975)	No. offspring of all stages	No. founding females	Negative?	New York, USA	DS	Spring nests. 1–3 foundresses. No statistics performed.	Litte (1977a)
<i>H. ligatus</i>	20 (1974)	No. cells	No. founding females	Negative?	New York, USA	DS	Spring nests. 1–3 foundresses. No statistics performed.	Litte (1977a)
<i>H. ligatus</i>	11 (1975)	No. cells	No. founding females	Negative?	New York, USA	DS	Spring nests. 1–3 foundresses. No statistics performed.	Litte (1977a)
<i>H. ligatus</i>	25 (1973)	No. offspring of all stages	No. females	Positive?	New York, USA	DS	Summer nests. 1–10 females per nest. No statistics performed.	Litte (1977a)
<i>H. ligatus</i>	28 (1974)	No. offspring of all stages	No. females	Negative?	New York, USA	DS	Summer nests. 1–10 females per nest. No statistics performed.	Litte (1977a)
<i>H. ligatus</i>	25 (1973)	No. cells	No. females	No effect?	New York, USA	DS	Summer nests. 1–10 females per nest. No statistics performed.	Litte (1977a)
<i>H. ligatus</i>	28 (1974)	No. cells	No. females	Negative?	New York, USA	DS	Summer nests. 1–10 females per nest. No statistics performed.	Litte (1977a)

Table 2. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>H. ligatus</i>	27	No. first brood offspring	No. founding females	No effect	Ontario, Canada	DS	Spring nests. 1–4 foundresses.	Packer (1986)
<i>H. scabiosae</i> (Rossi)	101	No. gynes + males produced	No. 'helpers' in B1 generation	No effect for 1–3 helpers, negative for >3	Switzerland	TPLS	Removal experiment estimated no. additional reproductives produced in generation B2 by each additional helper in generation B1.	Brand & Chapuisat (2014)
<i>Lasglossum aeneiventre</i> (Friese)	99	No. brood cells	No. females	Positive	Costa Rica	DS	1–14 females per nest.	Wcislo et al. (1993)
<i>L. balatum</i> (Cockerell)	33	No. brood cells	No. females	No effect	Japan	TPLS	1–4 females per nest. Mean cells/female peaks at 2 females.	Yagi & Hasegawa (2012)
<i>L. comagenae</i> (Knerer & Atwood)	26	No. brood cells	No. founding females	No effect	Nova Scotia, Canada	DS	1–4 females per nest.	Packer et al. (1989); Packer (1993)
<i>L. figueresi</i> Wcislo	30	No. brood cells	No. females	No effect	Costa Rica	DS	1–3 foundresses.	Wcislo et al. (1993)
<i>L. hemichalceum</i> (Cockerell)	25	No. immatures	No. females	No effect	Victoria, Australia	DS	1–18 females per nest.	Kukuk & Sage (1994)
<i>L. imitatum</i> (Smith)	28	No. brood cells	No. founding females	No effect*	Kansas, USA	DS	1–6 females per nest.	Michener & Wille (1961); Packer (1993)
<i>L. laevisimum</i> (Smith)	56	No. brood cells	No. founding females	Positive	Calgary, Alberta, Canada	DS	1–5 females per nest.	Packer (1993)
<i>L. lineare</i> (Schenck)	23	Final no. brood cells	No. founding females	No effect	Paris, France	DS	Spring nests. 1–6 females per nest.	Knerer (1983); Packer (1993)
<i>L. lineare</i>	24	Final no. brood cells	No. founding females	Negative	Dordogne, France	DS	Spring nests. 1–2 females per nest.	Knerer (1983); Packer (1993)
<i>L. malachurum</i> (Kirby)	40	Wet mass of sexuals produced by first-generation workers (WB1)	No. WB1 workers	Negative	Germany	FCLS	Mean no. WB1 workers = 4.25 ± 2.3.	Strohm & Bordon-Hauser (2003)
<i>L. malachurum</i>	15	Wet mass of sexuals produced by second-generation workers (WB2)	No. WB2 workers	No effect	Germany	FCLS	Mean no. WB2 workers = 7.5 ± 8.3.	Strohm & Bordon-Hauser (2003)
<i>L. zephyrum</i> (Smith)	78	Brood cells completed	No. founding females	Negative	Kansas, USA	DS	Laboratory-reared colonies.	Michener et al. (1971)

(Continues)

Table 2. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>Megalopta genalis</i> Meade-Waldo	23	No. new cells provisioned during 5 weeks	Mean no. females	No effect	Panama	Female no. censused daily in observation nests; cell no. determined by DS	Natural observation nests in field; post-emergence colonies.	Smith <i>et al.</i> (2007)
<i>M. genalis</i>	8	No. new brood cells per week	Mean no. females	No effect	Panama	Female no. censused daily in observation nests; cell no. determined by DS	Glass-topped observation nests in field; post-emergence nests.	Smith <i>et al.</i> (2007)
<i>M. genalis</i>	53	No. provisioned brood cells	No. females	Negative	Panama, 2003	DS	1–4 females per nest.	Smith <i>et al.</i> (2007)
<i>M. genalis</i>	25	No. provisioned brood cells	No. females	Negative	Panama, 2004	DS	1–4 females per nest.	Smith <i>et al.</i> (2007)
<i>M. genalis</i>	49	No. provisioned brood cells	No. females	Positive	Costa Rica, 2003	DS	1–4 females per nest.	Smith <i>et al.</i> (2007)
<i>M. genalis</i>	218	No. brood cells	No. females	Negative*	Jan 2007–2009	DS	Compared solitary <i>vs.</i> social. Broodless nests removed.	Smith <i>et al.</i> (2019)
<i>M. genalis</i>	156	No. brood cells	No. females	Negative*	Feb 2007–2009	DS	Compared solitary <i>vs.</i> social. Broodless nests removed.	Smith <i>et al.</i> (2019)
<i>M. genalis</i>	207	No. brood cells	No. females	Negative*	Mar 2007–2009	DS	Compared solitary <i>vs.</i> social. Broodless nests removed.	Smith <i>et al.</i> (2019)
<i>M. genalis</i>	119	No. brood cells	No. females	No effect*	Apr 2007–2009	DS	Compared solitary <i>vs.</i> social. Broodless nests removed.	Smith <i>et al.</i> (2019)
<i>M. genalis</i>	62	No. brood cells	No. females	Negative*	May 2007–2009	DS	Compared solitary <i>vs.</i> social. Broodless nests removed.	Smith <i>et al.</i> (2019)
<i>M. genalis</i>	29	No. brood cells	No. females	Negative*	July 2007–2009	DS	Compared solitary <i>vs.</i> social. Broodless nests removed.	Smith <i>et al.</i> (2019)
Totals		Genera = 4; species = 14		Negative = 16; No effect = 4				Data sets = 40

Note: for ease of reading, each of multiple data sets within a study is entered in its own row. **N** = sample size (number of colonies). **Output** = measure of colony output. **Input** = measure of colony input. **Effect of input on output** = slope of regression of output/input *versus* colony size. **Location** = where study was done. **Sampling type**: DS = destructive sampling; NDS = non-destructive sampling; FCLS = full-cycle longitudinal sampling; TPLS = two-point longitudinal sampling. **Notes** = relevant additional information. **References** = published source of data. An asterisk (*) indicates that we performed the statistical tests (see Section VI). A question mark (?) indicates a data set without a statistical basis for the effect; instead we used our best judgement in assessing the relationship based on the available data.

Table 3. Effect of colony size on *per-capita* productivity in Apidae: Xylocopinae

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
A. Ceratini								
<i>Ceratina australensis</i> (Perkins)	307	No. brood cells	No. females	Negative	Queensland, Australia	DS	1–2 females per nest.	Rehan <i>et al.</i> (2014)
B. Alodapini								
<i>Allocladopus dichroa</i> Strand	85	No. immatures	No. females	No effect	Western Cape Province, South Africa	DS	1–2 females per nest.	Tierney & Schwarz (2009)
<i>Braunsapis protuberans</i> Rcyes	?	No. immatures	No. females	No effect	Queensland, Australia	DS	August 2000.	Joyce & Schwarz (2007)
<i>B. protuberans</i>	?	No. immatures	No. females	No effect	Queensland, Australia	DS	October 2000.	Joyce & Schwarz (2007)
<i>B. protuberans</i>	?	No. immatures	No. females	No effect	Queensland, Australia	DS	November 2000.	Joyce & Schwarz (2007)
<i>B. protuberans</i>	?	No. immatures	No. females	No effect	Queensland, Australia	DS	January 2001.	Joyce & Schwarz (2007)
<i>B. protuberans</i>	?	No. immatures	No. females	No effect	Queensland, Australia	DS	February 2001.	Joyce & Schwarz (2007)
<i>B. puangensis</i> (Cockerell)	96	No. immatures	No. females	No effect	Fiji	DS	1–5 females per nest. May sampling.	Silva <i>et al.</i> (2016)
<i>B. puangensis</i>	22	No. immatures	No. females	No effect	Fiji	DS	1–5 females per nest. July sampling.	Silva <i>et al.</i> (2016)
<i>B. puangensis</i>	30	No. immatures	No. females	No effect	Fiji	DS	1–5 females per nest. Oct. sampling.	Silva <i>et al.</i> (2016)
<i>Brecinera elongata</i> (Rayment)	13	No. immatures	No. females	No effect*	Queensland, Australia	DS	1–8 females. Broodless nests removed. Aug. sampling.	Joyce & Schwarz (2006)
<i>B. elongata</i>	15	No. immatures	No. females	No effect*	Queensland, Australia	DS	1–8 females. Broodless nests removed. Oct. sampling.	Joyce & Schwarz (2006)
<i>B. elongata</i>	14	No. immatures	No. females	No effect*	Queensland, Australia	DS	1–8 females. Broodless nests removed. Nov. sampling.	Joyce & Schwarz (2006)
<i>B. elongata</i>	9	No. immatures	No. females	No effect*	Queensland, Australia	DS	1–8 females. Broodless nests removed. Feb. sampling.	Joyce & Schwarz (2006)
<i>Exoneura angophorae</i> (= <i>E. richardsoni</i>) Cockerell	44	No. immatures	No. females	Positive	Victoria, Australia	DS	Nests collected in Aug. 1–8 females per nest. Positive effect peaks at 3 females.	Schwarz <i>et al.</i> (1996)
<i>E. angophorae</i>	80	No. immatures	No. females	Positive	Victoria, Australia	DS	Nests collected in Dec. Positive effect peaks at 3 females.	Schwarz <i>et al.</i> (1996)

(Continues)

Table 3. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>E. angophorae</i>	45	No. immatures	No. females	No effect	Victoria, Australia	DS	Nests collected on 3 Jan.	Schwarz <i>et al.</i> (1996)
<i>E. angophorae</i>	42	No. immatures	No. females	No effect	Victoria, Australia	DS	Nests collected 16–22 Jan.	Schwarz <i>et al.</i> (1996)
<i>E. angophorae</i>	68	No. immatures	No. females	Positive*	New South Wales, Australia	DS	September nests. Broodless nests removed.	Bernaer <i>et al.</i> (2021)
<i>E. angophorae</i>	73	No. immatures	No. females	No effect*	New South Wales, Australia	DS	October nests. Broodless nests removed.	Bernaer <i>et al.</i> (2021)
<i>E. angophorae</i>	46	No. immatures	No. females	No effect*	New South Wales, Australia	DS	November nests. Broodless nests removed.	Bernaer <i>et al.</i> (2021)
<i>E. nigrescens</i> Friese	119	No. immatures	No. females	No effect	Victoria, Australia	DS	New nests with brood. 1–3 females per nest.	Schwarz (1994); Schwarz <i>et al.</i> (1998)
<i>E. nigrescens</i>	151	No. immatures	No. females	No effect	Victoria, Australia	DS	Reused nests with brood. 1–4 females per nest.	Schwarz (1994)
<i>E. nigrescens</i>	163	No. immatures	No. females	No effect	Victoria & South Australia, Australia	DS	Trap nests. 1–6 females.	Bull & Schwarz (1996)
<i>E. nigrescens</i>	500	No. immatures	No. females	Positive	Victoria, Australia	DS	Re-used nests only. 1–7 females. Positive effect peaks at 4 females.	Bull & Schwarz (1996)
<i>E. nigrescens</i>	89	No. immatures	No. females	No effect	Victoria, Australia	TPLS	Positive effect peaks at 3 females then declines.	Hogendoorn & Zammit (2001)
<i>E. nigrescens</i>	25	No. immatures	No. females	Positive	Victoria, Australia	TPLS	Nests protected from ant predation.	Zammit <i>et al.</i> (2008)
<i>E. nigrescens</i>	46	No. immatures	No. females	Positive	Victoria, Australia	DS	Positive effect rises from 1- to 3-female nests, then plateaus.	Silberbauer & Schwarz (1995)
<i>E. nigrescens</i>	122	No. immatures	No. females	Negative	Victoria, Australia	DS	Spring nests.	Stevens <i>et al.</i> (2007)
<i>E. nigrescens</i>	86	No. immatures	No. females	No effect	Victoria, Australia	DS	Summer nests.	Stevens <i>et al.</i> (2007)
<i>E. nigrescens</i>	131	Biomass of immatures	No. females	Negative*	Victoria, Australia	DS	Sept. sampling.	Stevens <i>et al.</i> (2007)
<i>E. nigrescens</i>	158	Biomass of immatures	No. females	Positive*	Victoria, Australia	DS	Nov. sampling.	Stevens <i>et al.</i> (2007)
<i>E. nigrescens</i>	87	Biomass of immatures	No. females	Positive*	Victoria, Australia	DS	Dec. sampling.	Stevens <i>et al.</i> (2007)

Table 3. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>E. robusta</i> Cockerell	250	No. immatures	No. females	No effect	Victoria, Australia	DS	New nests. 1–6 females per nest.	Schwarz (1994); Schwarz et al. (1998)
<i>E. robusta</i>	121	No. immatures	No. females	Positive	Victoria, Australia	DS	Reused nests. 1–8 females per nest. Positive effect peaks at 4 females.	Schwarz (1994); Schwarz et al. (1998)
<i>Exoneurella arenophila</i>	27	No. immatures	No. females	Negative*	Victoria, Australia	DS	Summer nests. 1–2 females. Broodless nests removed.	Dew et al. (2018a)
<i>E. eremophila</i>	141	No. immatures	No. females	Negative*	Victoria, Australia	DS	Autumn nests. 1–2 females. Broodless nests removed.	Dew et al. (2018a)
<i>E. setosa</i>	35	No. immatures	No. females	No effect*	Victoria, Australia	DS	Autumn nests. Broodless nests removed.	Dew et al. (2018b)
<i>E. setosa</i>	50	No. immatures	No. females	Negative*	Victoria, Australia	DS	Spring nests. Broodless nests removed.	Dew et al. (2018b)
<i>E. setosa</i>	102	No. immatures	No. females	Negative*	Victoria, Australia	DS	Summer nests. Broodless nests removed.	Dew et al. (2018b)
<i>Hasinamélissa minuta</i> (Brooks & Pauly)	23	No. brood	No. females	No effect	Madagascar	DS	1–6 females.	Schwarz et al. (2005)
<i>Macrogalea antanosy</i> Brooks & Pauly	17	No. immatures	No. females	No effect	Madagascar	DS	1–6 females. Unparasitized colonies only.	Smith & Schwarz (2006)
<i>M. ellipti</i> (Saussure)	46	No. immatures	No. females	No effect*	Madagascar	DS	1–7 females. Broodless nests removed.	Smith et al. (2006)
<i>M. Ramena</i> sp. (undescribed species collected near Ramena, Madagascar)	45	No. immatures	No. females	No effect*	Madagascar	DS	1–9 females. Positive effect peaks at 3 females. Broodless nests removed.	Smith et al. (2006)
<i>M. zanzibarica</i> Michener	69	No. immatures	No. females	Positive	Zanzibar Island, Tanzania	DS	1–10 females. Positive effect peaks at 2 females.	Tierney et al. (2002)
<i>M. sp.</i>	166	No. immatures	No. females	Positive	Malawi	DS	1–13 females. Positive effect increases to 5 females, then declines.	Thompson & Schwarz (2006)
Totals:		Genera = 8; species = 16		Negative = 7; No effect = 28; Positive = 11				Data sets = 46

Note: see Table 2 for explanation of entries.

Table 4. Effect of colony size on *per-capita* productivity in Apidae: Apinae

Genus species	<i>N</i>	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
A. <i>Bombus</i>								
<i>Bombus auricomus</i> (Robertson)	14	No. sexuals produced	No. workers produced	No effect*	Nebraska, USA	FCLS	Colonies reared in observation boxes; allowed to free-forage.	Webb (1961) Data from table 75
<i>B. griseocollis</i> (De Geer)	21	No. sexuals produced	No. workers produced	Positive*	Nebraska, USA	FCLS	Most colonies reared in observation boxes; allowed to free-forage.	Webb (1961) Data from table 49
<i>B. pensylvanicus</i> (De Geer)	20	No. sexuals produced	No. workers produced	Positive*	Nebraska, USA	FCLS	Most colonies reared in observation boxes; allowed to free-forage.	Webb (1961) Data from table 26
<i>B. lucorum</i> (Linnaeus)	20	No. of sexuals produced	Maximum no. workers in colony	No effect*	Switzerland	FCLS	Colonies housed in concrete cylinders placed underground, censused every 2–3 days. Allowed to free-forage.	Müller & Schmid-Hempel (1992)
<i>B. lucorum</i>	20	Biomass of sexuals produced	Maximum no. workers in colony	No effect*	Switzerland	FCLS	Colonies housed in concrete cylinders placed underground, censused every 2–3 days.	Müller & Schmid-Hempel (1992)
<i>B. terricola</i> Kirby	32	No. of sexuals produced	Total no. workers	Negative*	New Brunswick, Canada	FCLS	Colonies started in laboratory from spring queens, then moved to field. New workers marked every other day	Owen <i>et al.</i> (1980)
<i>B. terricola</i>	32	Biomass of sexuals produced	Total no. workers	Negative*	New Brunswick, Canada	FCLS	Colonies started in laboratory from spring queens, then moved to field. New workers marked every other day.	Owen <i>et al.</i> (1980)
Totals: Genera = 1; species = 5								
Negative = 2; No effect = 3; Positive = 2								
B. <i>Apis mellifera</i>								
<i>Apis mellifera</i> Linnaeus	25	Scaled brood area	No. workers	No effect*	British Columbia, Canada	TPLS	Founding swarms.	Lee & Winston (1985)
<i>A. mellifera</i>	15	Biomass of sealed brood	No. workers	No effect*	British Columbia, Canada	TPLS	Founding swarms.	Lee & Winston (1985)
<i>A. mellifera</i>	50	No. brood cells per day	No. workers	Negative	Louisiana, USA	TPLS	Experimentally constituted founding swarms of 2,300, 4,500, 9,000, 17,000 and 35,000 bees. Colonies of 4500 workers produced most brood cells/worker.	Harbo (1986)
<i>A. mellifera</i>	50	Mass of brood + honey per day	No. workers	Positive	Louisiana, USA	TPLS	Founding swarms. Colonies of 17,000 and 35,000 produced the most honey/worker.	Harbo (1986)
<i>A. mellifera</i>	12	Worker comb built (cm ²)	No. workers	Negative*	New York, USA	TPLS	Artificially sized founding swarms.	Rangel & Seeley (2012)

Table 4. (Cont.)

Genus species	<i>N</i>	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>A. mellifera</i>	12	Drone comb built (cm ²)	No. workers	Positive*	New York, USA	TPLS	Artificially sized founding swarms.	Rangel & Seeley (2012)
<i>A. mellifera</i>	12	Scaled worker brood (cm ²)	No. workers	No effect*	New York, USA	TPLS	Artificially sized founding swarms.	Rangel & Seeley (2012)
<i>A. mellifera</i>	12	Scaled drone brood (cm ²)	No. workers	No effect*	New York, USA	TPLS	Artificially sized founding swarms.	Rangel & Seeley (2012)
<i>A. mellifera</i>	12	Honey stored	No. workers	No effect*	New York, USA	TPLS	Artificially sized founding swarms.	Rangel & Seeley (2012)
<i>A. mellifera</i>	12	No. workers lost	No. workers	No effect*	New York, USA	TPLS	Artificially sized founding swarms.	Rangel & Seeley (2012)
Totals:		Genera = 1; species = 1		Negative = 2; No effect = 6; Positive = 2				Data sets = 10

Note: see Table 2 for explanation of entries.

that ergonomic efficiency decreases or increases (respectively) with increasing colony size.

A third approach is to fit a power model written as $P = aS^c$. The exponent, c , determines the concavity of the resulting curve. Taking logarithmic transformations of both sides of the equation has the benefit of straightening curvilinear data, allowing the application of linear regression (e.g. see Tschinkel, 1999). The equation becomes $\log P = \log a + c \log S$. A value of the slope $c = 1$ indicates a linear relationship between colony size and productivity, i.e. no effect of colony size on efficiency. If the slope is significantly less than or greater than 1, we conclude that efficiency decreases or increases, respectively, with increasing colony size (Tschinkel, 1999).

Since all three methods rely on regression analysis, it is necessary that the assumptions underlying the regression are met, or the tests for significance may not be reliable. For example, there can be problems with non-homogeneity of variance (heteroscedasticity) when using *per-capita* productivity as the response variable [e.g. see Karsai & Wenzel (1998) and Jeanne & Nordheim (1996)]. In such cases, the second or third methods described above are preferable and avoid this issue. A second issue raised by Michener (1964) that has received some discussion (Cole, 1984) revolves around the y -intercept when total colony productivity is plotted against colony size. If the estimated y -intercept is different from 0 (even if not significantly so) this will have an impact on the plot of the *per-capita* values that are calculated from this model and regressed on colony size. Since in most studies where the y -intercept is reported it is positive, this alone will tend to make the slope in regressions using *per-capita* productivity, m , more negative (often only very slightly so) than perhaps it should be. The second method avoids this issue, although there is an analogous effect when analysing data using the log-transformed regression approach described above. Despite this, we interpret studies using all three analysis approaches.

In Tables 2–8 the effect of colony size on ergonomic efficiency is scored as ‘negative,’ ‘positive,’ or ‘no effect,’ based on statistical analyses reported in the cited references. Although most of the papers we cite reported *per-capita* productivity, a handful provided results in the form of total productivity as a function of colony size. For most studies, we use the statistical results and interpretations of the authors. However, in some studies, we performed statistical comparisons ourselves, either because the authors did not perform an analysis of colony size and ergonomic efficiency, or because we took issue with their methodology. In the latter event we either removed colonies that we thought should not be included [e.g. queenless colonies (Scharf *et al.*, 2012a; Kramer *et al.*, 2014); broodless colonies (e.g. Tierney *et al.*, 2002); see Section VI below], or used a re-calculated superior output metric [pupal biomass rather than brood count (Spradbery, 1971; Lee & Winston, 1985); for details, see Table S1]. For our statistical analyses, we used the two approaches described below in the meta-analyses (Section VI), using 95% confidence intervals to determine if the predicted effect overlapped with the expected value for no effect. If the effect reported in a table comes from our own

Table 5. Effect of colony size on *per-capita* productivity in Vespidae: Vespinae (yellowjackets)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>Vespa germanica</i> (Fabricius)	14	Dry mass of pupae	No. workers	No effect*	England	DS	Colonies sampled August 10–31, 1961. Masses estimated using data in Blackith (1958).	Spradbery (1971) Data from table 3
<i>V. vulgaris</i> (Linnaeus)	27	Dry mass of pupae	No. workers	No effect*	England	DS	Colonies sampled August 11–31, 1961. Queen pupae appear in mid-August. Masses estimated using data in Archer (2012, p. 140–141).	Spradbery (1971) Data from table 2
Totals			Genera = 1; species = 2	Negative = 0; No effect = 2; Positive = 0				Data sets = 2

Note: see Table 2 for explanation of entries.

statistical analyses, we indicate this with an asterisk in Tables 2–8 summarizing our findings. Statistical analyses were performed in R version 4.0.2 (R Core Team 2020).

For all methods it is important to take sample size into account. A non-significant test outcome (positive or negative) may simply reflect that the sample size was too small to find significance. Thus, the numbers of non-significant test outcomes are not necessarily evidence against the Michener pattern, and a comparison of the numbers of significant positives and significant negatives is more useful. These issues are dealt with more rigorously by the formal meta-analyses in Section VI.

In the sections below, we address the results of our review by taxonomic group.

(2) Bees

(a) Colletid and halictid bees

A number of studies of eusocial bees in the socially diverse family Halictidae have measured *per-capita* productivity while controlling for seasonal and ontogenetic effects (Table 2). Most of the studies are based on DS or TPLS, and in most cases the proxy for productivity is the number of provisioned brood cells. Because in a number of species of these bees the first females to emerge are smaller than later-emerging individuals (Chole, Woodard & Bloch, 2019), simple counts of provisioned cells may underestimate productivity. Brand & Chapuisat (2014) used an experimental approach to estimate the effect of helpers on *per-capita* productivity in colonies of *Halictus scabiosae* (Rossi). They removed single individuals from the B1 (helper) generation and measured the impact on the numbers of B2 (reproductive) offspring produced. Over colonies of all sizes (1–11 B1 helpers), the effect of adding one helper had a negative effect; for colonies with 1–3 helpers, each additional helper produced on average 0.72 additional B2 offspring. However, when the greater biomass of gynes and males over helpers was factored into the analysis, the average *per-capita* productivity of a helper in small colonies approached 1. That is, by this more realistic metric, colony size appeared to have no effect on *per-capita* output.

Of the 40 data sets reported in Table 2 (14 species in four genera), group size had a positive effect on *per-capita* output in four, a neutral effect in 20 and a negative effect in 16. The excessive number of negative effects, compared to positive, suggests a possible Michener effect in this group.

(b) Ceratinine and allodapine bees

Xylocopine bees in these two tribes nest in hollow twigs and stems (Michener, 2000). *Ceratina australensis* (Perkins), a mass-provisioner, is facultatively social, with some nests containing two females (Rehan et al., 2014). The allodapines progressively feed their larvae, and most species show some degree of subsociality or simple eusociality (Schwarz et al., 1998). Most of the data reported in Table 3 are based on DS of colonies in the founding stage. In some of the studies a few nests contained no brood but still contained one or

Table 6. Effect of colony size on *per-capita* productivity in Vespidae: Polistinae (independent-founding polistine wasps)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
A. <i>Polistes</i>								
<i>Polistes annularis</i> (Linnaeus)	40	No. cells	No. founding females	Negative*	Georgia, USA	TPLS	Nests collected at end of pre-emergence stage.	Krispyn (1979) Data from tables 8–10
<i>P. annularis</i>	40	No. cells at autumn census (end of season)	No. founding females at spring census	No effect*	Georgia, USA	TPLS	End of season census.	Krispyn (1979) Data from tables 8–10
<i>P. annularis</i>	40	No. cells	No. founding females	Negative*	Georgia, USA	DS	Nests collected at first cell capping.	Chao (1984) Data from tables 1 & 2
<i>P. aurifer</i> de Saussure	14	No. offspring produced	No. founding females	Negative	California, USA	FCLS	Total offspring produced at end of season.	Liebert et al. (2005)
<i>P. carolina</i> (Linnaeus)	17	No. cells	No. founding females	Negative*	Texas, USA	DS	All nests collected 26 April, close to end of larval phase of pre-emergence stage.	Seppa et al. (2002)
<i>P. chinensis</i> Pérez	12	Dry mass of reproductives produced	No. workers produced	Negative*	Japan	DS	Colonies collected at end of season, 1–5 September 1976.	Suzuki (1981)
<i>P. dominula</i>	29	No. cells	No. founding females	Negative*	Italy	TPLS	Nests censused one week after foundation.	Turillazzi et al. (1982)
<i>P. dominula</i>	29	Mass of nest + brood	No. founding females	Negative*	Italy	TPLS	Nests censused one week after foundation.	Turillazzi et al. (1982)
<i>P. dominula</i>	21	No. cells	No. founding females	Negative*	Italy	TPLS	Nests censused one month after foundation.	Turillazzi et al. (1982)
<i>P. dominula</i>	21	Mass of nest + brood	No. founding females	No effect*	Italy	TPLS	Nests censused one month after foundation.	Turillazzi et al. (1982)
<i>P. dominula</i>	65	No. cells added per day	No. founding females	Negative	Spain	FCLS	Nests censused every 2–4 days.	Grinsted & Field (2018)
<i>P. dominula</i>	41	No. cells	No. founding females	Negative	Germany	TPLS	Nests censused at end of pre-emergence stage.	Hocherl & Tautz (2015)
<i>P. dominula</i>	41	No. pupae	No. founding females	Negative	Germany	TPLS	Nests censused at end of pre-emergence stage.	Hocherl & Tautz (2015)
<i>P. dominula</i>	41	No. cells	No. founding females	Negative	Germany	TPLS	Nests censused at end of season.	Hocherl & Tautz (2015)
<i>P. dominula</i>	30	No. cells	No. founding females	Negative	Massachusetts, USA	DS	Nests censused at end of pre-emergence stage.	Liebert & Starks (2006)
<i>P. dominula</i>	66	No. brood	No. founding females	Negative*	Spain	NDS	Pre-experimental census April 1. Each time point contains different colonies.	Shreeves et al. (2003)
<i>P. dominula</i>	53	No. brood	No. founding females	Negative*	Spain	NDS	Pre-experimental census April 21.	Shreeves et al. (2003)

(Continues)

Table 6. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>P. dominula</i>	26	No. brood	No. founding females	No effect*	Spain	NDS	Pre-experimental census April 28.	Shreeves <i>et al.</i> (2003)
<i>P. fuscatus</i>	30	No. cells	No. founding females	No effect for one- vs. two-foundress colonies, then negative?	Michigan, USA	DS	Nests censused at end of pre-emergence stage. No statistics performed.	West-Eberhard (1969) Data from table 5
<i>P. fuscatus</i>	97	No. pupae	No. founding females	No effect	Ontario, Canada	FCLS	Nests in protected and unprotected field shelters. Censused at end of pre-emergence stage.	Gibo (1978)
<i>P. fuscatus</i>	46	No. reproductives	No. founding females	Negative	Ontario, Canada	FCLS	Protected sites. No. reproductives estimated from end-of-season counts of cells that produced adults.	Gibo (1978)
<i>P. fuscatus</i>	14	No. reproductives	No. founding females	Negative	Ontario, Canada	FCLS	Exposed sites. No. reproductives estimated from end-of-season counts of cells that produced adults.	Gibo (1978)
<i>P. infuscatus</i>	34	No. cells	No. founding females	Negative?	Colombia	DS	Nests censused at end of pre-emergence stage. No statistics performed.	West-Eberhard (1969) Data from table 12
<i>P. metricus</i> Say	49	No. workers eclosing	No. founding females	No effect	Illinois, USA	DS	Output measured as no. females emerging during days 1–24 after collection.	Metcalf & Whitt (1977)
<i>P. snelleni</i> de Saussure	31	No. males produced	No. workers produced	Negative*	Hokkaido, Japan	DS	Nests collected end of season; sex and caste produced by each cell based on cell size.	Inagawa <i>et al.</i> (2001)
<i>P. snelleni</i>	30	No. gyns produced	No. workers produced	Negative*	Hokkaido, Japan	DS	As above.	Inagawa <i>et al.</i> (2001)
<i>P. snelleni</i>	19	No. males produced	No. workers produced	No effect*	Kanto, Japan	DS	As above.	Inagawa <i>et al.</i> (2001)
<i>P. snelleni</i>	19	No. gyns produced	No. workers produced	No effect*	Kanto, Japan	DS	As above.	Inagawa <i>et al.</i> (2001)

Table 6. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>P. snelleni</i>	32	No. males produced	No. workers produced	No effect*	Nagano, Japan	DS	As above.	Inagawa <i>et al.</i> (2001)
<i>P. snelleni</i>	32	No. gynes produced	No. workers produced	No effect*	Nagano, Japan	DS	As above.	Inagawa <i>et al.</i> (2001)
<i>B. Mischocyttarus cassununga</i> (von Ihering)	51	No. cells	No. founding females	Negative*	Minas Gerais, Brazil	FCLS	Censused at end of pre-emergence stage.	Castro <i>et al.</i> (2014)
<i>M. drevaseni</i> (de Saussure)	14	No. cells	No. founding females	Negative*	Pará, Brazil	FCLS	Censused at hatch of first larva.	Jeanne (1972) Data from table 19
<i>M. drevaseni</i>	7	No. cells	No. founding females	Negative*	Pará, Brazil	FCLS	Censused at eclosion of first worker.	Jeanne (1972) Data from table 19
<i>M. labiatus</i> (Fabricius)	25	No. cells	No. founding females	Negative?	Colombia	FCLS	Censused at nest age 5 days. 1–5 founding females. No statistics performed.	Litte (1981) Data from table 2
<i>M. labiatus</i>	25	No. cells	No. founding females	Negative?	Colombia	FCLS	Censused at first egg hatch. 1–9 founding females. No statistics performed.	Litte (1981) Data from table 2
<i>M. labiatus</i>	17	No. cells	No. founding females	Negative?	Colombia	FCLS	Censused at first pupation. No statistics performed.	Litte (1981) Data from table 2
<i>M. labiatus</i>	12	No. cells	No. founding females	Negative?	Colombia	FCLS	Censused at end of pre-emergence stage. 1–5 founding females. No statistics performed.	Litte (1981) Data from table 2
<i>M. labiatus</i>	12	No. pupae	No. founding females	No effect?	Colombia	FCLS	Censused at end of pre-emergence stage. 1–5 founding females. No statistics performed.	Litte (1981) Data from table 2
<i>M. labiatus</i>	12	New pupae/day	No. founding females	No effect?	Colombia	FCLS	Censused at end of pre-emergence stage. 1–4 founding females. No statistics performed.	Litte (1981) Data from table 2
<i>M. mexicanus</i> (de Saussure)	75	Mean no. cells built during first 3 weeks	No. founding females	No effect?	Florida, USA	FCLS	1 and 2 founding females only. No statistics performed.	Litte (1976) Data from table 11
<i>M. mexicanus</i>	88	Mean no. cells built between first pupation and first adult emergence	No. founding females	No effect?	Florida, USA	FCLS	1–6 founding females. No statistics performed.	Litte (1976) Data from table 11

(Continues)

Table 6. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>M. mexicanus</i>	88	Mean no. cells built up to first adult emergence	No. founding females	Negative?	Florida, USA	FCLS	1–6 founding females. No statistics performed.	Litte (1976) Data from table 11
<i>M. mexicanus</i>	88	Mean no. pupae at first adult emergence	No. founding females	No effect?	Florida, USA	FCLS	1–6 founding females. No statistics performed.	Litte (1976) Data from table 11
<i>M. mexicanus</i>	39	Mean no. cells built during first 3 weeks after adult emergence	No. working adults	No effect?	Florida, USA	FCLS	Data in table 14 are based on no. working adults, including queen. No statistics performed.	Litte (1976)
<i>M. mexicanus</i>	10	No. cells added/female/day	Mean no. founding females	No effect	Florida, USA	FCLS	Manipulated founding-group size; pleometrotic groups only. Censused on day of first cell capping.	Clouse (2001)
<i>M. mexicanus</i>	10	No. offspring added/female/day	Mean no. founding females	Positive	Florida, USA	FCLS	Manipulated founding-group size; pleometrotic groups only. Censused on day of first cell capping.	Clouse (2001)
<i>M. mexicanus</i>	11	Mass of nest material added/female/day to day of first capped cell	Mean no. founding females	Negative	Florida, USA	FCLS	Manipulated founding-group size; pleometrotic groups only.	Clouse (2001)
<i>M. mexicanus</i>	11	Mg. offspring added/female/day to day of first capped cell	Mean no. founding females	Negative	Florida, USA	FCLS	Manipulated founding-group size; pleometrotic groups only.	Clouse (2001)
<i>C. Ropalidia</i>								
<i>Ropalidia fasciata</i> (F.)	25	No. cells on April 25–26, 1982	No. founding females	No effect*	Okinawa, Japan	TPLS		Itô (1983)
<i>R. fasciata</i>	48	No. cells on April 13–14, 1983	No. founding females	Negative*	Okinawa, Japan	TPLS	Dominance interactions among cofoundresses are milder than among <i>Polistes</i> spp.	Ito (1985)
<i>R. fasciata</i>	156	No. potential foundresses produced	No. founding females	No effect	Okinawa, Japan	FCLS	Data from table 9 (excludes failed colonies).	Ito & Irioka (2008)
<i>R. fasciata</i>	16	No. cells/day/female to end of egg stage	No. founding females	No effect	Okinawa, Japan	FCLS		Kojima (1989)

Table 6. (Cont.)

Genus species	<i>N</i>	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>R. fasciata</i>	16	No. cells/day/ female to end of larval stage	No. foundresses	Positive	Okinawa, Japan	FCLS		Kojima (1989)
<i>R. fasciata</i>	12	No. cells/day/ female to end of pupal stage	No. founding females	No effect	Okinawa, Japan	FCLS		Kojima (1989)
<i>Ropalidia marginata</i> (Lepeletier)	48	Weighted no. brood at eclosion of first worker	No. founding females	Negative	India	FCLS	Colonies reared in laboratory, but with access to outside.	Brahma et al. (2018)
<i>D. Belongaster</i>								
<i>Belongaster petiolata</i> (DeGeer)	37	No. cells in the nest at eclosion of first worker	No. founding females	No effect	South Africa	FCLS	2–10 foundresses of surviving colonies.	Keeping (1989)
<i>B. petiolata</i>	37	No. eggs in the nest at eclosion of first worker	No. founding females	Negative	South Africa	FCLS	2–10 foundresses of surviving colonies.	Keeping (1989)
<i>B. petiolata</i>	37	No. larvae in the nest at eclosion of first worker	No. founding females	No effect	South Africa	FCLS	2–10 foundresses of surviving colonies.	Keeping (1989)
<i>B. petiolata</i>	67	No. pupae in the nest at eclosion of first worker	No. founding females	Positive	South Africa	FCLS	2–10 foundresses of surviving colonies.	Keeping (1989) Data from fig. 9.6B
Totals:		Genera = 4; species = 16	Negative = 33; No effect = 23; Positive = 3				Data sets = 59	

Note: see Table 2 for explanation of entries.

Table 7. Effect of colony size on *per-capita* productivity in Vespidae: Polistinae: Epiponini (swarm-founding wasps)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>Parachartegus fraternus</i> (Gribodo)	35	No. cells in nest	No. founding females	No effect	Costa Rica	DS	Nests collected 25 days after founding.	Bouwma <i>et al.</i> (2006)
<i>P. fraternus</i>	33	Brood dry mass	No. founding females	No effect	Costa Rica	DS	Nests collected 25 days after founding.	Bouwma <i>et al.</i> (2006)
<i>Polybia occidentalis</i> (Olivier)	19	No. cells in nest	No. founding females	Positive	Costa Rica	DS	Nests collected 25 days after founding.	Jeanne & Nordheim (1996)
<i>P. occidentalis</i>	19	Brood dry mass	No. founding females	Positive	Costa Rica	DS	Nests collected 25 days after founding.	Jeanne & Nordheim (1996)
<i>P. occidentalis</i>	66	No. cells in nest	No. founding females	No effect	Costa Rica	DS	Nests collected 25 days after founding.	Bouwma <i>et al.</i> (2005)
<i>P. occidentalis</i>	53	Brood dry mass	No. founding females	No effect	Costa Rica	DS	Nests collected 25 days after founding.	Bouwma <i>et al.</i> (2005)
Totals:			Genera = 2; species = 2	Negative = 0; No effect = 4; Positive = 2				Data sets = 6

Note: see Table 2 for explanation of entries.

more females. Because it is likely that these cases are the result of predation by ants (Zammit *et al.*, 2008), we considered these as failed colonies and excluded them from our survey. We also excluded studies that did not make it clear if broodless nests were excluded from their analyses of *per-capita* productivity.

Numerous studies on these bees show that rates of broodlessness are higher among single-female nests than among multi-female nests, suggesting that brood defence is an important benefit of cooperative nesting (reviewed in Schwarz *et al.*, 1998). However, even when broodless nests were excluded, some species had higher *per-capita* productivity in two-female nests than in single-female nests, indicating that reduction of the risk of brood loss is not the only benefit of cooperation (Tierney *et al.*, 2002).

Of the 46 data sets in Table 3 (16 species in 8 genera), 11 show a positive effect of group size, 28 showed no effect, and seven reported the negative Michener pattern.

(c) *Bombus*

In addition to Webb's dissertation on several bumble bee species (Webb, 1961) (Fig. 4), Owen, Rodd & Plowright (1980) and Müller & Schmid-Hempel (1992) provided data on *per-capita* productivity for one additional species each. Results among the three studies could not be more disparate (Table 4A). One possibility for the differences in the effect of worker number on *per-capita* output of sexuals is that they represent actual species differences. However, the fact that all three of Webb's species showed the same positive effect of colony size on PCP suggests that this is not the case. An alternative possibility is that the species do not differ in this regard, and that the different outcomes reflect subtle procedural differences among the three studies. For example, while focusing on sex-ratio differences between their study and Webb (1961), Owen *et al.* (1980) pointed out that Webb may have missed finding smaller colonies in the field, thereby skewing his samples towards larger colonies. However, it is unclear how such a bias could produce a positive effect of colony size on *per-capita* biomass of sexuals produced. Another possibility also suggested by Owen *et al.* (1980) is that Webb may have undercounted males produced early in the season. If these early males are produced particularly heavily by small colonies, then this could underestimate the productivity of small colonies. Owen *et al.* (1980) also acknowledge that because their colonies were started in the laboratory and then allowed to free-forage, queens that were too weak to have founded colonies in the wild may have been allowed to reproduce, possibly skewing the distribution of *per-capita* productivity across colony size.

Müller & Schmid-Hempel (1992) started colonies of *B. lucorum* in the laboratory from wild-caught queens, then moved them to the field after a few workers had emerged. Colonies were censused every second or third night for number of workers and sexuals. Both biomass and number of

Table 8. Effect of colony size on *per-capita* productivity in Formicidae (ants)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>Diacamma</i> sp.	11	No. workers enclosing over 21 days centred on maximum no. enclosing	No. workers	No effect	Japan	FCLS		Nakata (2000)
<i>Leptothorax acervorum</i> (Fabricius)	246	Dry biomass new workers + gynes + males produced	Original number of workers	No effect*	England	TPLS	Monogynous and polygynous colonies.	Chan & Bourke (1994); Chan <i>et al.</i> (1999)
<i>L. acervorum</i>	162	Dry mass workers + sexuals produced	No. workers	No effect*	Abensberg, Germany	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>L. muscorum</i>	151	Dry mass workers + sexuals produced	No. workers	Negative*	Abensberg, Germany	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>Myrmica punctiventris</i>		Dry mass workers + sexuals produced	No. workers	No effect*	New York, USA	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>Phaidole multispina</i> Wilson	31	No. pupae	No. adults	Negative*	Costa Rica	DS	Nests collected in Feb, Mar, May, Aug.	Kaspari & Byrne (1995)
<i>P. multispina</i>	10	Biomass of alates	No. adults	No effect*	Costa Rica	DS	Nests collected in Feb, Mar, May, Aug.	Kaspari & Byrne (1995)
<i>P. nigricula</i> Wilson	121	No. pupae	No. adults	No effect *	Costa Rica	DS	Nests collected in Feb, Mar, May, Aug.	Kaspari & Byrne (1995)
<i>P. nigricula</i>	29	Biomass of alates	No. adults	Negative*	Costa Rica	DS	Nests collected in Feb, Mar, May, Aug.	Kaspari & Byrne (1995)
<i>P. rugiceps</i> Wilson	33	No. pupae	No. adults	No effect*	Panama	DS	Nests collected Jun, Jul, Sep–Nov.	Kaspari & Byrne (1995)
<i>P. rugiceps</i>	8	Biomass of alates	No. adults	No effect*	Panama	DS	Nests collected Jun, Jul, Sep–Nov.	Kaspari & Byrne (1995)
<i>P. rugiceps</i>	15	No. pupae	No. adults	No effect*	Costa Rica	DS	Nests collected in Feb, Mar, May, Aug.	Kaspari & Byrne (1995)
<i>P. rugiceps</i>	10	Biomass of alates	No. adults	No effect*	Costa Rica	DS	Nests collected in Feb, Mar, May, Aug.	Kaspari & Byrne (1995)
<i>P. specularis</i> Wilson	41	No. pupae	No. adults	No effect*	Costa Rica	DS	Nests collected in Feb, Mar, May, Aug.	Kaspari & Byrne (1995)
<i>P. specularis</i>	12	Biomass of alates	No. adults	Negative*	Costa Rica	DS	Nests collected in Feb, Mar, May, Aug.	Kaspari & Byrne (1995)
<i>Pogonomyrmex badius</i> (Latreille)	22	Total no. brood	No. workers	Negative	Florida, USA	DS	Nests excavated May, Jul, Oct, Jan	Byrne (1995)
<i>P. badius</i>	30	Total mass seeds	Colony mass	No effect	Florida, USA	DS	Nests excavated May, Jul, Oct, Jan.	Tschinkel (1999)
<i>P. badius</i>	30	Total mass seeds	No. dark (older) workers	Positive	Florida, USA	DS	Nests excavated May, Jul, Oct, Jan.	Tschinkel (1999)
<i>P. badius</i>	29	Total mass fat	Colony mass	Positive	Florida, USA	DS	Nests excavated May, Jul, Oct, Jan.	Tschinkel (1999)

(Continues)

Table 8. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>P. occidentalis</i> (Cresson)	31–60	Dry mass of reproductives	Colony size (mound volume)	Negative	Colorado, USA	NDS	Field colonies sampled in each of 4 years. Alates captured after mating flights induced by watering.	Cole & Wiernasz (2000)
<i>Solenopsis invicta</i> Buren	89	Total energy content (J) per day	Colony size (total worker biomass)	No effect	Florida, USA	DS	Colonies excavated throughout one annual cycle.	Tschinkel (1993)
<i>Tennohoxax albipennis</i>	116	No. brood	No. adults	Negative	England	DS	Colonies collected on one day. If reproductive brood was present in some colonies, output could be underestimated.	Franks <i>et al.</i> (2006)
<i>T. allardycei</i> (Mann)	28	No. brood	No. workers	No effect	Florida, USA	DS	Field colonies brought to laboratory for censusing.	Cole (1984)
<i>T. americanus</i>	31	Dry mass workers + sexuals produced	No. workers + slaves	No effect	New York, USA	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>T. americanus</i>	18	Dry mass workers + sexuals produced	No. workers + slaves	No effect*	West Virginia, USA	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>T. crassispinus</i>	45	Dry mass workers + sexuals produced	No. workers	No effect*	Abensberg, Germany	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>T. crassispinus</i>	93	Dry wt. workers + sexuals produced	No. workers	Positive*	Regensburg, Germany	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>T. longispinosus</i>	275	Dry mass workers + sexuals produced	No. workers	Negative*	New York, USA	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>T. longispinosus</i>	182	Dry mass workers + sexuals produced	No. workers	Negative*	West Virginia, USA	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>T. nylanderii</i>	453	Dry mass workers + sexuals produced	No. workers	No effect*	Sommerhausen (South), Germany	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>T. nylanderii</i>	187	Dry mass workers + sexuals produced	No. workers	No effect*	Sommerhausen (North), Germany	DS	Queenless colonies removed.	Kramer <i>et al.</i> (2014)
<i>T. nylanderii</i> (Foerster)	40	No. brood	No. workers	No effect*	Germany	DS	Colonies reared in laboratory. Queenless colonies removed.	Scharf <i>et al.</i> (2012b)
<i>T. nylanderii</i>	60	Biomass of pupae	No. workers	Negative*	Germany	DS	Colonies collected in July–Aug. Queenless colonies removed.	Scharf <i>et al.</i> (2012b)
<i>Tetramorium caespitum</i> (Linnaeus)	27	Live mass of sexuals	Live mass of workers	Positive*	England	NDS	Analysis based on mean data for 27 colonies each sampled over 3–6 years. Worker numbers estimated by mark and recapture; total sexual production estimated by repeated collection.	Brian & Elmes (1974)

Table 8. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>Trachymyrmex septentrionalis</i> (McCook)	28	Biomass (wet) of reproductives	No. workers	No effect*	Florida, USA	DS	Colonies collected 1–3 weeks prior to the mating flight.	Beshers & Traniello (1994)
<i>T. septentrionalis</i>	27	Biomass (wet) of reproductives	No. workers	Negative*	New York, USA	DS	Colonies collected 1–3 weeks prior to the mating flight.	Beshers & Traniello (1994)
<i>Linepithema humile</i> (Mayr)	24	No. brood produced after 25 days	1 queen with 10, 30, and 300 workers	No effect	Spain (colonies moved to laboratory)	TPLS	Experimentally constituted, laboratory-reared colonies of 10, 30, or 300 workers with 1, 3, and 6 queens and no brood.	Luque et al. (2013)
<i>L. humile</i>	48	No. brood produced after 25 days	3 and 6 queens with 10, 30, and 300 workers	Negative	Spain (colonies moved to laboratory)	TPLS	Experimentally constituted, laboratory-reared colonies of 10, 30, or 300 workers with 1, 3, and 6 queens and no brood.	Luque et al. (2013)
<i>L. humile</i>	12	No. brood produced after 2 months	Final no. workers	No effect	California, USA	TPLS	Experimentally constituted laboratory-reared colonies of 1,000–10,000 workers with 1 queen/1,000 workers.	Hee et al. (2000)
<i>Formica neofibribaris</i> Emery	211	No. cocoons	No. workers	No effect	Colorado, USA	NDS	Non-reproductive-stage field colonies. Worker numbers and cocoon production estimated by mark and recapture. 6 years of data.	Billick (2001)
<i>Lasius flavus</i> (Fabricius)	8	Alate queens	No. workers	Positive*	England	NDS	Field colonies. Worker number estimated by mark (P ³²) and recapture.	Odum & Pontin (1961)
<i>L. niger</i> (Linnaeus)	8	Dry mass of reproductives	No. workers	No effect*	The Netherlands	NDS	Strandvlakte habitat (early-stage succession of primary coastal dune valleys). Worker numbers estimated by mark and recapture; all reproductives were aspirated from mound.	Boomsma et al. (1982)
<i>L. niger</i>	9	Dry mass of reproductives	No. workers	No effect*	The Netherlands	NDS	Kobbeduinen habitat (sheltered coastal dune valley). Worker numbers estimated by mark and recapture; all reproductives were aspirated from mound.	Boomsma et al. (1982)

(Continues)

Table 8. (Cont.)

Genus species	N	Output	Input	Effect of input on output	Location	Sampling type	Notes	Reference
<i>L. sakagami</i> (Yamauchi and Hayashida)	11	No. larvae	No. workers	Positive*	Japan	DS	Summer sampling.	Yamauchi <i>et al.</i> (1982)
<i>L. sakagami</i>	20	Biomass of larvae	No. workers	No effect*	Japan	DS	Winter 1977 sampling.	Yamauchi <i>et al.</i> (1982)
Totals:		Genera = 12; species = 24		Negative = 12; No effect = 27; Positive = 6				Data sets = 45

Note: see Table 2 for explanation of entries.

sexuals produced suggested no effect of colony size on efficiency (Table 4A).

Taken together, the seven *Bombus* data sets in Table 4A show two positive, three neutral and two negative effects of group size on efficiency.

(d) *Apis*

While some studies of honey bees purport to support the hypothesis (Free & Racey, 1968; Accorti, Tarducci & Luti, 1991), they fail to meet our criteria because they do not take account of potential differences in amounts of stored food in the nest at the start of the season. The two studies we know of that avoid this problem started with founding swarms lacking comb or stored food (Table 4B). Lee & Winston (1985) measured the amount of sealed brood per worker at first worker emergence and found no support for the hypothesis. The amount of honey accumulated was not measured. The results of the other (Harbo, 1986) mirrored those of Farrar (1937), described above (Section IV.3); that is, brood reared *per capita* was higher in small colonies, while honey stored *per capita* was higher in large colonies. Harbo's measure of adjusted mass gain of the colony in mg/bee/day, an attempt to measure all output by including all honey and pollen used to rear brood, consumed by adults, and stored in the nest, showed a positive effect of colony size, increasing in colonies of 2300–9000 workers, then remaining constant up to sizes of 35,000 workers.

A more recent study directly measured all forms of worker output (Rangel & Seeley, 2012). The data again show how the chosen metric of output can lead to results that either support, refute, or are ambivalent towards the hypothesis. Rangel & Seeley (2012) set up colonies with founding swarms of three sizes: 5000, 10000, and 15000 workers ($N = 4$ of each size). They measured parameters of colony growth and development throughout the first year, but for our analysis, we selected each colony parameter after 18–20 days, before new workers eclosed, thereby accounting for the output of the workers present in the initially constituted founding swarms. The amount of worker comb built per worker was negatively correlated with colony size (Fig. 9A), in accordance with the hypothesis. Drone comb built, however, was positively correlated with colony size, against the hypothesis (Fig. 9B). None of the other colony parameters (sealed worker brood, sealed drone brood, honey stores amassed, workers lost) varied significantly with colony size (Fig. 9C–F), and so do not support the hypothesis.

Of the 10 *Apis* data sets in Table 4B, two showed a positive effect of group size on output, while six were neutral and two negative. The single metric that most completely captured total output – mg of brood plus mg honey produced per day – showed a positive response to colony size (Harbo, 1986).

This analysis shows especially well how the form of worker output measured will influence the conclusion. Although one could try to convert the different parameters to a single metric of colony performance (e.g. it takes 6.25 kg of honey to produce 1 kg of beeswax; Weiss, 1965), those conversions

would not account for associated costs, such as the time and energy a worker invests in wax secretion and comb building. Unfortunately, there is no easily applicable common currency for all forms of worker output for honey bees.

(3) Wasps

(a) *Vespine wasps*

Spradbery (1971) calculated *per-capita* productivity of *Vespula vulgaris* (Linnaeus) based on data from destructively sampled colonies in England between 11 and 31 August 1961. Using the total numbers of eggs, larvae, and pupae in the nests as output and numbers of workers at collection as input, he concluded that *per-capita* productivity was strongly negatively related to colony size (his fig. 10).

This method is flawed. It rests on at least one of two assumptions. The first is that each individual brood item – whether an egg, larva or pupa – represents the same investment (e.g. in biomass or energy) by the colony. This is clearly not true. The second is that these three stages of brood occur in the same relative proportions across colonies of all sizes. This is not supported by Spradbery's data. Colonies collected 11–31 August (his table 2) show a strong negative effect of colony size on the number of eggs in the nest per worker (eggs/worker = $0.7 - 0.000134 * \text{workers}$; $N = 27$; $P < 0.001$). By contrast, the number of pupae per worker shows no relation to colony size (pupae/worker = $1.249 - 0.000058 * \text{workers}$; $N = 27$; $P = 0.394$). That is, compared to smaller colonies, larger colonies have a higher ratio of pupae to eggs. Put another way, the mean biomass of individual brood is higher in larger colonies. This means that Spradbery's counts of brood underestimated the more relevant measure of productivity – brood biomass – of large colonies relative to small ones.

To improve on this analysis, we converted Spradbery's data on numbers of gyne, male, and worker pupae to total biomass of pupae [we used Archer's (2012) data on dry mass of *V. vulgaris* adult queens, males, and workers] to estimate colony productivity in terms of pupal biomass. The regression slope of log-transformed total pupal biomass on log-transformed worker number is slightly, but non-significantly, greater than 1, consistent with no effect of worker number on efficiency (Fig. 5A; Table 5).

Although a complete accounting of brood productivity should include the biomass of larvae as well as pupae, this was not possible in this case because Spradbery did not break down the numbers of larvae in his nests by instar. However, a reasonable assumption is that the numbers of the largest (fourth and fifth instar) larvae per worker more closely reflect the relationship to colony size described above for pupae than for eggs, and therefore that pupal biomass is a more accurate proxy for total brood biomass than is the number of brood.

We performed the same analysis for *V. germanica* (Fabricius), using data from Spradbery (1971) and biomass data from Blackith (1958), and obtained a similar result (Table S1). Thus, we conclude that there is no effect of colony

size on ergonomic efficiency for either species (Fig. S1; Table 5).

(b) *Independent-founding wasps*

Michener did not consider productivity in *Polistes* or other independent-founding wasps, because, at the time, there were no published data available for this group. In recent decades a number of studies of productivity in *Polistes*, *Mischocyttarus*, *Ropalidia*, and *Belonogaster* have been published, mostly on founding-stage colonies (Table 6). Of the 59 data sets on independent-founding Polistinae in Table 6, three show a positive effect of colony size, 23 show no effect, and 33 a negative effect. While these results might appear to support the hypothesis of lower worker efficiency in larger groups, such a conclusion comes with a caveat. Founding groups of *Polistes* are made up of cooperative breeders rather than a queen and workers (Leadbeater *et al.*, 2011; Avila & Fromhage, 2015; Grinsted & Field, 2018). Helpers engage in a trade-off of their helping effort against their expectation of inheriting the alpha position of egg-layer. Conflict over access to direct reproduction is common and typically leads to the establishment of a dominance hierarchy, which can be modelled as a queue for the inheritance of the alpha position (Cant & Field, 2005). Because of the effect of dominance rank on expected future reproductive success, higher-ranked individuals are predicted to be less willing than lower-ranked ones to invest in rearing the current dominant's offspring at the expense of a reduction of their own chance of inheriting the reproductive position (Cant & Field, 2001, 2005). Further, conflicts tend to escalate more, and individuals of a given rank tend to work at lower rates, in larger founding groups compared to smaller ones (Grinsted & Field, 2018). A related prediction – that subordinates of a given rank should contribute less effort in larger than in smaller groups – has been supported for *Polistes dominula* (Cant & Field, 2001). Additional support for the model comes from empirical studies showing an inverse correlation between overt reproductive conflict and colony growth rate (West-Eberhard, 1969; Shakarad & Gadagkar, 1995). Removal of the queen increases the rate of dominance interactions, resulting in a pronounced negative effect on group productivity (West-Eberhard, 1969; Souza, Lino-Neto & Nascimento, 2017) (see also Gobin *et al.*, 2003). Indeed, some reproductive skew models explain how resources get expended on reproductive conflicts to the detriment of total colony output (Reeve & Keller, 2001). In sum, because a founding group does not consist of a queen plus one or more females behaving altruistically as workers, founding groups of these wasps do not provide valid tests of the hypothesis. A similar argument can be made for the Stenogastrinae (Francescato *et al.*, 2002; Sumner *et al.*, 2002; Fanelli, Boomsma & Turillazzi, 2005; Field, Cronin & Bridge, 2006). In some polistine species, workers are still totipotent and overt dominance and conflict over direct reproduction continue well into the post-emergence stage (e.g. West-Eberhard, 1969; Jeanne, 1972; Gadagkar, 2001). Thus, such conflict could contribute to the reduced PCP reported in larger groups of workers.

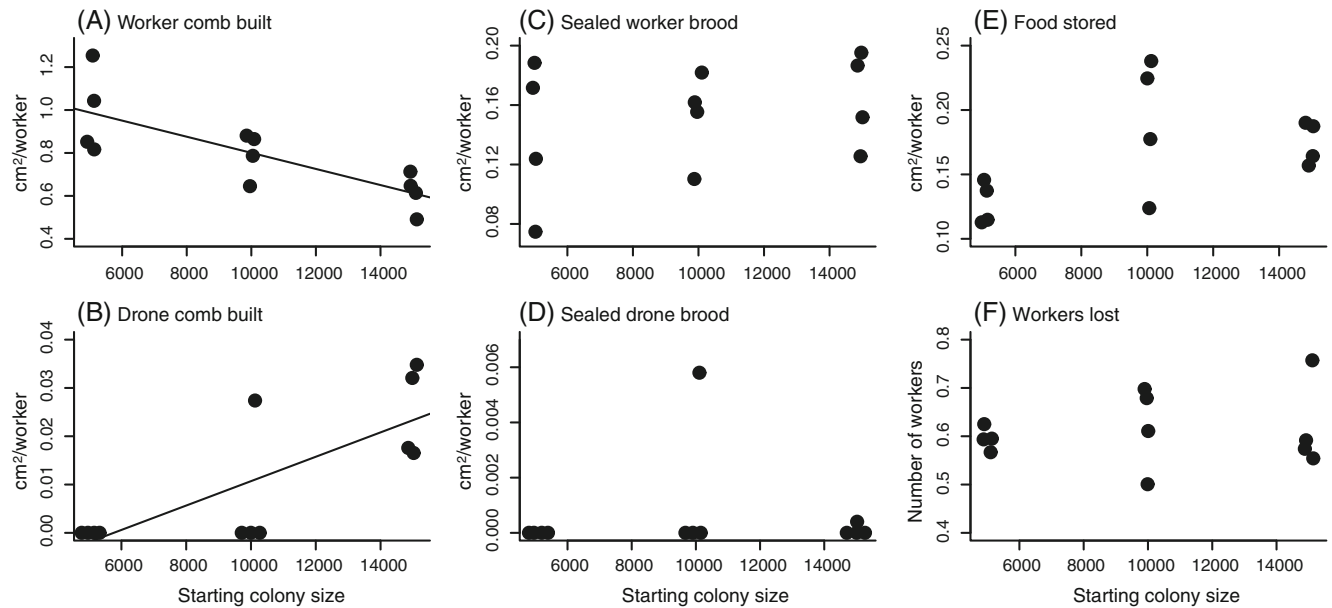


Fig. 9. *Per-capita* output of *Apis mellifera* colonies. Data from Rangel & Seeley (2012) were analysed to show how the chosen form of worker output leads to results that either support, refute, or are neutral to Michener's pattern. Each colony parameter is measured in cm² of comb area (A–E) or number of workers (F) and is plotted on a *per-capita* basis (colony parameter/starting colony size). Starting colony size = number of workers in the swarm. Linear regression was used to determine how each colony parameter responded to colony size. Parameters were measured 18–20 days after the colonies were established, so that new workers had not yet eclosed. Black lines show statistically significant linear regressions (worker comb built: $F_{1,10} = 15.45$, $P < 0.005$, $r^2 = 0.57$; drone comb built: $F_{1,10} = 13.80$, $P < 0.005$, $r^2 = 0.54$; sealed worker brood: $F_{1,10} = 0.92$, $P > 0.05$, NS, $r^2 = -0.01$; sealed drone brood: $F_{1,10} = 0.01$, $P > 0.05$, NS, $r^2 = -0.10$; food stored: $F_{1,10} = 3.18$, $P > 0.05$, NS, $r^2 = 0.17$; workers lost: $F_{1,10} = 0.22$, $P > 0.05$, NS, $r^2 = -0.08$).

(c) *Swarm-founding wasps*

Despite the limitations of the data (Richards & Richards, 1951) analysed by Michener, the epiponine wasps are ideal for a test of the hypothesis that ergonomic efficiency declines with increasing group size. Because founding swarms of a given species vary widely in size (Forsyth, 1981; Jeanne & Nordheim, 1996; Karsai & Wenzel, 1998; Bouwma *et al.*, 2003b, 2006), the effect of group size on *per-capita* output can be measured over a wide size range for this precisely delimited colony stage. In each of three TPLS investigations on two species, the colony cycle was reset to the founding stage by forcing adult populations out of their nests (Jeanne & Nordheim, 1996; Bouwma, Howard & Jeanne, 2005; Bouwma *et al.*, 2006). The resulting absconding swarms initiated new colonies that were allowed to develop for 25 days, just short of the egg-to-adult development time, and were then collected to assess colony size and productivity. The results can be translated to a rate: output per female per day. Colony size was the final number of adult females. The rate of adult attrition during the period is independent of the size of the founding swarm in these wasps (Bouwma *et al.*, 2006). Productivity was measured as (i) the size of the nest (number of brood cells) constructed by the founding swarm [nests constructed by the founding swarm are completed in the first 2–3 weeks after founding and are not expanded until well into the ergonomic stage (Jeanne & Bouwma, 2004; Loope & Jeanne, 2008)], and (ii) the total biomass (dry) of brood in the nest at the end of the fixed

period of development. Between them, these two proxies capture all of the output of colonies during the founding stage, and so are valid estimates of ergonomic efficiency. Two of the data sets showed a positive effect of colony size, while the other four showed no effect (Table 7). For *Polybia occidentalis*, a typical small colony (278 females) in the study produced 3.6 brood cells and 10.4 mg of brood per founding female, whereas a typical large colony (719 adults) produced 6.3 cells and 19.4 mg of brood per female (Jeanne & Nordheim, 1996; Jeanne, 1999). In an attempt to reinterpret Jeanne and Nordheim's results so as to provide support for the hypothesis, Karsai & Wenzel (1998) ignored the significant year effect, included colonies that were known outliers, and drew their conclusion without statistical support [see Bouwma *et al.* (2006) for further discussion]. Therefore, we use the results of the original Jeanne and Nordheim analysis, which provided evidence for increasing, not decreasing, *per-capita* productivity with increasing colony size. Note that in the meta-analysis (Section VI), the results from each year are analysed separately, both showing effect size CIs that overlap with 1, suggesting a neutral effect (Fig. S1).

Taken together, the results for the swarm-founding wasps provide no support for the hypothesis that *per-capita* productivity decreases with increasing colony size for this taxon. This suggests no negative effect detectable at the colony level of foragers in larger colonies having to travel farther to find resources and no negative effect of having to build larger

nests. The per-cell cost of nest construction is a constant function of nest size in *P. occidentalis* (Jeanne & Nordheim, 1996).

(4) Ants

For several reasons, studies of ants are especially problematic when it comes to investigating ergonomic efficiency and results must be interpreted with care. First, colony cycles of ants last several years, so that even studies based on collections made on a single date (e.g. Franks *et al.*, 2006) cannot rule out ontogenetic effects. Small colonies are likely to be in the early ergonomic stage, with their main output the production of worker brood, the usual proxy for output, whereas large colonies collected on the same day may be in the reproductive stage, with a large fraction of input investment directed to the production and maintenance of sexuals (Figs 2 & 6).

Second, for species with polymorphic workers, scoring output as numbers of worker brood may yield artificially low estimates of ergonomic efficiency across colony size if, for example, larger, more mature colonies produce higher percentages of the larger, more costly, soldier-subcaste workers than do smaller colonies. In a field experiment on *Solenopsis invicta* Buren, the number of new workers produced per worker per day decreased with increasing colony size, but the mass or energy content produced per worker per day showed no decrease (Tschinkel, 1993). The same caveat applies to counts of alates as output because the costs of production of gynes and males typically differ from each other and exceed those of workers. Measuring output in terms of biomass or energy content is a way of accounting for such differences, but this is rare in the studies we cite (see Table 8).

Third, artificially constituted colonies housed in the laboratory, common in studies of ants, can also be problematic. Porter & Tschinkel (1985) found that small colonies of *S. invicta* produced 50% more brood per worker (measured as gram/gram and mg/worker) than colonies four times as large. However, the authors pointed out that because each experimental colony was assembled with a single mature queen, varying numbers of workers, and no brood, the *per-capita* output of the larger colonies could have been limited by queen fecundity (oviposition rates were not measured), rather than by decreasing ergonomic efficiency.

Finally, drawing conclusions about ergonomic efficiency from laboratory studies can be risky because the unnatural conditions and housing configurations may create artificial inefficiencies (Brian, 1956a; Tschinkel, 2006; Leitner, Lynch & Dornhaus, 2019).

For all these reasons, it is especially difficult to determine whether a particular study of productivity in ants provides data that accurately measure ergonomic efficiency. Table 8 includes studies that appear to control for these sources of potential bias. We excluded studies that lacked sufficient methodological detail to determine whether our criteria were met. Some of those we include still warrant caveats. For example, *per-capita* productivity in larger colonies of litter-nesting species may be limited by nest-site size rather than by decreasing ergonomic efficiency (Cole, 1984; Kaspari & Byrne, 1995; Kramer *et al.*, 2014)

Studies of ants also illustrate the importance of selecting the most appropriate output metric. For example, effects

differ substantially between alate counts and pupal counts for several species of *Pheidole* (Kaspari & Byrne, 1995), and while brood number suggested a negative effect in *Pogonomyrmex badius* (Tschinkel, 1999), stored seeds and fat content exhibited neutral or positive effects (Table 8).

The only other major multi-species test of the hypothesis comes from Kramer *et al.* (2014), who assessed colony-size effects on productivity in 12 large data sets from eight species of small-colony ants (*Temnothorax* spp., *Leptothorax* spp, *Myrmica* spp. and *Harpagoxenus* spp.). Using the slope of log-transformed productivity on colony size as an analysis method, they concluded that most species exhibit declining efficiency in larger colonies. The authors generously gave us access to their raw data, and we report here the results of a similar analysis, but with the removal of queenless colonies, as such colonies are likely to exhibit lower efficiency (Cole, 1986), which could obscure size effects among queen-right colonies. For nine of the 11 data sets we re-analysed, slopes were higher following queenless colony removal (mean difference = 0.098, paired *t*-test: $t_{10} = 3.42$, $P < 0.01$), resulting in a less negative pattern than found in the original study (see Fig. S1 and Table S1 for details of re-analysis). Thus, the inclusion of queenless colonies represents yet another methodological bias that increases the chances of observing a Michener paradox pattern.

Of the 45 analyses on ants (24 species in 12 genera), six showed a positive effect of colony size on ergonomic efficiency, 27 showed no effect, and 12 a negative effect.

(5) Overall summary of review results

Combining the five taxonomic groups with larger colony sizes and more complex sociality (*Apis mellifera*, *Bombus* spp., *Vespa* spp., Epiponini, Formicidae), 42 show a neutral effect of colony size on efficiency, while 12 show a positive and 16 show a negative response. Thus, we find a similar number of positive and negative effects, with the majority (42/70) of data sets showing no effect. For small-colony species (Colletidae + Halictidae, Xylocopinae, independent-founding Polistinae), we find an excess of negative effects: nearly half of effects are neutral (71/145), but there are many more negative effects (56) than positive (18), suggesting a bias in the direction of Michener's pattern (but note that this bias is not present in the Xylocopinae when considered alone; Table 3).

In total, the available studies suggest substantial variation, but no bias toward negative effects in the more complex, large-colony taxa, with negative biases primarily in Colletidae + Halictidae and in the independent-founding paper wasps.

VI. META-ANALYSIS OF POST-MICHENER STUDIES

To account for the varying sample sizes, effect magnitudes, and the non-independence of the above data sets, we performed two formal meta-analyses statistically to synthesise

these results into overall estimates of the effect of colony size on ergonomic efficiency (Nakagawa & Santos, 2012).

(1) Meta-analysis methods

(a) Data collection

We conducted two different meta-analyses reflecting the two major types of statistical comparisons we found in the literature. In the first, colony size was measured as a continuous variable (hereafter referred to as the continuous meta-analysis or CMA). In the second, colonies were categorized into discrete size groups of either 1 female or >1 female (hereafter referred to as the discrete meta-analysis or DMA). When we had the raw data available, data sets in which fewer than half of the colonies had a colony size of just one female were included in the CMA; the remaining data sets were included in the DMA. This threshold balanced the desire to include as many data sets as possible in the CMA, so that small-colony and large-colony species were included in the same meta-analysis, with the desire to avoid fitting regressions to very lopsided colony-size distributions in the case of data sets with many single-female colonies.

For the DMA, numerous studies with discrete colony-size classes reported means and SDs for multiple classes, and we acknowledge that simply comparing single-female to multi-female nests obscures the potential complexity of size effects on productivity at different colony sizes. However, we were unable to develop a suitable alternative effect size that would apply across most data sets, and numerous studies have already reported results in this format, so we adopted it as the best possible approach (see Section VI.1d). With some exceptions, the two types of meta-analysis correlated with colony size, with studies of small-colony species using discrete size categories, and those of large-colony species using continuous measures of size. We obtained raw data from tables, from figures using the WebPlotDigitizer program (Rohatgi, 2020), or directly from authors. We used only raw data obtained from authors that were published in some form in the cited references. Reported descriptive or test statistics were used when raw data were unavailable.

(b) Inclusion criteria

Data sets reported in our meta-analyses are a subset of those included in Tables 2–8. We considered all studies discovered in the literature searches described above (Section V.1a), but excluded studies for which we were unable to obtain necessary data or test statistics. In two cases, we excluded certain colonies within data sets. First, queenless colonies were removed from data sets in Chan, Hingle & Bourke (1999), Scharf *et al.* (2012a), and Kramer *et al.* (2014), as queenlessness can substantially influence colony behaviour and productivity (Landolt, Akre & Greene, 1977; Cole, 1986; Keiser *et al.*, 2018; Smith, 2018). Second, we removed colonies with zero brood from some halictid and allodapine data sets (20 data sets from seven studies), either by obtaining raw data sets and omitting them, or by adjusting mean, SD, and

N using Welford's formulae (Welford, 1962) to remove broodless colonies from PCP summary statistics. Zero-productivity colonies were rare for the continuous colony-size meta-analysis but were common in some small-colony bee species in the discrete meta-analysis (e.g. Silva, Stevens & Schwarz, 2016; Smith, Kapheim & Wcislo, 2019). In allodapine and halictid bees, broodless colonies are disproportionately single-female colonies and may be the result of ant predation (Zammit *et al.*, 2008), thus representing colony survival failure, rather than low ergonomic productivity. Removing them is conservative for our purposes; broodless nests occur disproportionately in single-female nests, and so removing them boosts apparent PCP in small-colony nests, increasing the chances of detecting a Michener pattern (see also Fig. 3). Because it is also possible that some such colonies result from low productivity rather than colony failure, we conducted a second version of the DMA that included broodless colonies, as well as three studies (seven data sets) that included broodless nests in reported summary statistics but for which raw data were unavailable (Tierney *et al.*, 1997; Chenoweth & Schwarz, 2007; Tierney & Schwarz, 2009). The number of broodless colonies in each such data set is reported in Table S2 and ranged from <5% to over 50% of the nests, depending on the study. Polistine wasp studies that included failed (depredated or abandoned) colonies were omitted when we could not obtain raw data to remove broodless colonies (e.g. Tibbetts & Reeve, 2003; Tindo, Kenne & Dejean, 2008).

(c) Multiple outputs

Numerous studies reported more than one form of output for the same set of colonies (e.g. brood number and brood biomass, or brood number and amount of food stored). A few studies reported multiple incomplete outputs, such as production of males and production of gynes, or independent food storage and brood-production data. For these studies, we included multiple outputs in the meta-analysis, but coded them as 'partial' under the *output completeness* moderator (see Section VI.1e). For two papers, Spradbery (1971) and Lee & Winston (1985), we were able to use the raw data reported in the text to calculate a biomass estimate of output in addition to the count data reported in the text (see Table S1 for details). For the data sets with both brood count and biomass data for the same set of colonies, we used only the more accurate and less-biased output measure (biomass) in the meta-analysis (Fig. 5). We included a random effect of study to account for multiple outputs from within a study in the overall effect estimate.

(d) Effect sizes

We conducted separate meta-analyses for continuous and discrete colony size data sets. For the CMA, we used the slope of the regression of log-transformed output on log-transformed input. This effect size can conveniently be compared to 1.0 (no effect of colony size on efficiency) and requires no standardization or transformation of inputs or

outputs on different scales. It also avoids the heteroscedasticity problem found in many *per-capita*-productivity data sets (see Section V.1*b*). We typically calculated the slope, slope variance, and sample size from raw data, but for a few data sets used the estimates reported by authors instead (Tschinkel, 1993, 1999; Franks *et al.*, 2006).

For the DMA, we compared PCP of single-female colonies to multi-female colonies using a standardized mean-difference effect size e (Aoki, 2020). This effect size is similar to Cohen's d and reflects the difference between the two group means divided by a measure related to the pooled standard deviation, but accounts for unequal variances between groups using a correction based on the method of Welch's t -test (Aoki, 2020). We used the `es.para.e()` function in the `es.dif` package (Aoki, 2020) to estimate e and its variance from means, SDs, and sample sizes extracted from figures or text, or in some cases calculated by us from raw data. Numerous studies included more than two colony-size categories and reported summary statistics in figures or tables. For these, if we could not obtain the raw data, we generated a pooled mean, SD, and sample size for all multi-female groups using the `pool.groups` function in the `dmatar` package in R (Harrer *et al.*, 2019). Multi-female group-size information was available in all studies included in the DMA, but we chose to combine multi-female nests into a single PCP estimate in order to allow for a single, comparable effect size to be calculated for all data sets. The effect sizes, sample sizes, and source information for each data set are included in Tables S1 and S2.

(e) Moderator variables

For the CMA, we used two moderator variables to explore the role of output measure on the colony size–productivity relationship: *output type* and *output completeness*. Output type was coded as ‘offspring count’, ‘offspring mass or energy’, ‘stored food’, or ‘nest area’, with ‘offspring count’ set as the intercept. Output completeness was coded as ‘complete’ when it involved an estimate of the total production (offspring of all castes + stored food if the species stores food) during the time period considered, or ‘partial’ if it included only a partial measure of output (e.g. sexuals produced in a species also investing in workers, or brood produced in a species that also stores food). The intercept was set to ‘complete’. In the CMA we also included a moderator variable for taxonomic group with eight levels: Halictidae, Xylocopinae, *Bombus*, *Apis mellifera*, Vespinae, independent-founding Polistinae, Epiponini, Formicidae. In the DMA, there was insufficient variation among studies to score output type or output completeness, so we included only one moderator variable, taxonomic group, with three levels: Halictidae + Colletidae, Xylocopinae, independent-founding Polistinae. In both cases, Halictidae was used as the intercept.

(f) Phylogeny

It is important to account for shared evolutionary history in meta-analyses, as this generates non-independence among data collected from related species (Adams, 2008; Nakagawa &

Santos, 2012). A common approach that accounts for this non-independence is to generate a covariance matrix from an ultrametric phylogenetic tree, and then incorporate this as a random effect in the meta-analysis model (Nakagawa & Santos, 2012). We created two phylogenies, one for each meta-analysis. Phylogenies were generated by hand in Mesquite (Maddison & Maddison, 2021) using estimates of node ages (in millions of years ago) from taxon-specific molecular phylogenies. Specifically, we used published chronograms for Allodapini (Rehan, Leys & Schwarz, 2012), *Lasioglossum* (Gibbs *et al.*, 2012), *Bombus* (Hines, 2008), Apoidea tribes and families (Branstetter *et al.*, 2017; Shell *et al.*, 2021), Vespidae (Menezes, Lloyd & Brady, 2020), non-myrmicine ants (Moreau *et al.*, 2006), Myrmicinae (Ward *et al.*, 2015; Prebus, 2017), and we used Branstetter *et al.* (2017) for the divergence between ant, bee, and wasp clades. For several species, close relatives were substituted (e.g. congeners when only one species of the genus was present in our analysis). Unknown topologies were entered as polytomies. Divergence dates for several nodes within genera (indicated by asterisks in Fig. S2) were not available in any published trees. For these nodes, we entered arbitrary ages estimated as roughly half the age of the genus or subgenus, or species complex (e.g. *Tennothorax nylanderii* and *T. crassispinus*). Branch lengths were then computed from node ages, and the trees were imported into R.

(g) Meta-analysis models

We used the function `rma.mv()` in the package *metafor* (Viechtbauer, 2010) to build random-effects meta-analytical models for our two subsets of data sets. Species, study, data set (nested within study), and the variance–covariance matrix from the phylogeny were included as random effects. Taxonomic group as well as output type and output completeness (only in the CMA) were entered as a modulator variable to determine if they significantly influenced effect sizes. Models were also created for taxonomic subgroups to obtain summary estimates for each subgroup, and for all of the large-colony taxa in the CMA together (excluding Halictidae, Xylocopinae and the independent-founding Polistinae). In the CMA we also separately examined the subsets of studies with complete output measures and those with brood mass output. Finally, we assessed the effects of moderator variables in the large-colony taxa. We also created a DMA model that included the three studies (12 data sets) on xylocopine species with an unknown number of broodless colonies that were omitted from the original DMA model, and the broodless colonies that were removed from seven studies on xylocopine and halictid species included in the original DMA (20 data sets). For each model we performed a Q -test to determine whether there was residual heterogeneity in effect sizes beyond that expected by chance. For our study, a significant result would indicate that there are likely to be true differences in effect sizes among data sets; the null hypothesis is that there is one common effect size shared by all data sets, with noise creating the apparent differences in effect sizes among them. We also calculated I^2 , a measure of the

percentage of variance in effect size that is due to true heterogeneity in effect size rather than chance (Higgins & Thompson, 2002), using the approach described on the *metafor* website [https://www.metafor-project.org/doku.php/tips:i2_multilevel_multivariate; Accessed 9/13/2021].

(2) Meta-analysis results

The CMA of 109 effect sizes from 49 species suggests substantial and significant heterogeneity in effect sizes that is not due to sampling variance, with high I^2 values and significant Q -tests for most taxa (Figs 10 & S1; Table S3). When considering all moderator predictors together, *Bombus* had significantly higher slopes than Halictidae (the intercept), although no other differences between moderator levels were significant (Table S4). However, some trends are apparent, with small-colony species like the halictids and independent-founding paper wasps showing negative trends, while other groups such as *Bombus* and Epiponini show positive trends (Figs 10 & S1; Table S4). The large majority of individual effect sizes overlap 1.0 (the expectation for no effect), and the overall slope estimate across all taxa after accounting for phylogeny is 0.95, with confidence intervals that overlap 1.0. The same overall result holds when considering only studies that measure brood mass (Table S5), or only studies that include a 'complete' estimate of output (Table S6). When considering only the large-colony taxa (excluding Halictidae, Xylocopinae and independent-founding Polistinae), the estimate is even closer to 1 ($N=66$ data sets, estimated slope = 0.99, 95% CI: 0.89–1.10; Tables S7 & S8). Taken together, this strongly supports the idea that for most social insect species, particularly those in the large-colony taxonomic groups, colony size does not negatively affect ergonomic efficiency.

The DMA of 54 data sets from 24 species comparing single-female with multi-female nests in small-colony species revealed a trend towards a negative effect of colony size on PCP, although this was not significant (95% CI of summary effect size overlaps zero; Figs 11 & S3; Table S9). Confidence intervals for the independent-founding paper wasps summary effect did not overlap zero, indicating a strongly negative effect, and the summary effect for halictids was also negative, although not significantly so (Fig. S3). Taxonomic groups did not differ significantly ($Q_M = 3.2273$, $df = 2$, $P = 0.20$; Fig. S3; Table S10). However, there was substantial and significant heterogeneity in effect sizes (Figs 11 & S3), rather than a uniform negative effect across studies and taxa, and particularly in the xylocopine bees, numerous data sets showed either no effect or a positive effect of colony size. When broodless colonies are included in the analysis, the estimated effect size for Halictidae + Colletidae becomes less negative and that for Xylocopinae actually becomes positive, although both confidence intervals are extremely wide and overlap zero (Fig. S4; Table S11). This occurs because the vast majority of broodless nests are single-female nests, and thus their inclusion lowers PCP for these nests while leaving the PCP for multi-female nests the same. The changes in individual studies that result from this inclusion, and the number of broodless colonies in each data set, can be seen

by comparing Figs S3 and S4. It remains unclear whether including broodless colonies is appropriate for our test, given the uncertain cause of broodlessness (i.e. low productivity *versus* nest failure due to predation).

Taken together, these results suggest that most groups do not meet the prediction of the hypothesis, but that there is likely to be declining ergonomic efficiency with increasing colony size in small-colony taxa like halictids and independent-founding polistines. This finding is consistent with the hypothesis that conflict over direct reproductive opportunities reduces ergonomic benefits of social living, as these groups typically exhibit strong conflict among totipotent females (Cant & Field, 2005; Leadbeater *et al.*, 2011; also see Section VII). Survival benefits to small-colony sociality, well documented in the literature (Gibo, 1978; Litte, 1981; Bull & Schwarz, 1996; Schwarz *et al.*, 1998), could alleviate the selective disadvantage of a reduction in PCP in social colonies and may resolve the paradox in these groups. Importantly, in large-colony social insects, where direct-fitness options for workers are limited, we see no evidence of declining *per-capita* productivity with increasing colony size.

The critical importance of accurate output measures and measurement is highlighted by the observed bias created by using brood counts instead of brood masses in data sets for which we have both measures (Fig. 5). In the CMA, we detected no significant effects of output type or completeness (Table S4). However, when considering only the large-colony taxa, 'stored food' had a significantly higher slope than 'off-spring count' (Table S8); 'nest area' was significantly lower, but this is based on a single data point. For output completeness, 'partial output' studies were estimated to have a slope of productivity on colony size that is 0.20 lower than that for 'complete output' estimates, though this result was not significant ($P = 0.14$; Table S8). Although we did not detect significant differences in the CMA between incomplete and complete outputs, nor between brood mass and brood count, the paired within-study comparison of brood mass and count has a much greater power to detect such a bias, and we stress the importance of considering all forms of output when empirically testing Michener's paradox in the future.

Our meta-analyses were marked by high heterogeneity among data sets, and this variation was likely due to true differences rather than to sampling variance, given the significant Q -tests and high I^2 values for most taxonomic groups (Figs 10 & 11). This suggests that many factors influence apparent efficiency–size relationships, including observation decisions (output definition, accuracy of measurement, control for season and developmental stage, geographic and temporal range considered), and biological realities (resource variation, population, and species differences).

VII. MECHANISMS

Investigating efficiency at the level of individuals or small groups can reveal the behavioural mechanisms, or proximate

causes (Naug, 2001), behind the colony-level responses reviewed above (Robson & Traniello, 1999). As colony size increases during ontogenetic development, what behavioural changes occur among workers to bring about a change in the colony's ergonomic efficiency? If there is a true positive or negative effect of size on efficiency, what happens at the individual level to explain it?

There are reasons why *per-capita* colony efficiency (rates of brood production) might decrease as colony size increases. Identifying the sources of negative feedback that cause this has long been recognized as a central question in colony population dynamics (Wilson, 1971; Tschinkel, 1988). A number of authors, beginning with Michener (1964), have suggested ways that larger colonies might experience decreasing *per-capita* output. These include: (i) declining fecundity of the queen (Michener, 1964). Tschinkel (1988), for example, found a decline of efficiency in the stimulation of queen fecundity by larvae in larger colonies of the fire ant, leading to a decline in the per-larva reproductive rate as colony size and larval population increase. (ii) Larger colonies may be labour-saturated and retain a larger reserve force, indicated by increasing numbers of inactive workers (Dornhaus, Holley & Franks, 2009; Waters *et al.*, 2010; Kramer *et al.*, 2014; Stroeymeyt *et al.*, 2017). (iii) Colony members engage in reproductive conflict, reducing *per-capita* productivity (see discussion of independent-founding polistines in Section V). (iv) Large colonies allocate a larger percentage of workers from brood care into a reserve population (Porter & Tschinkel, 1985). (v) Ineffectiveness of some worker castes at rearing larvae. In monomorphic ants, the larger the worker, the less effective it is at brood rearing. In large colonies of fire ants, up to 70% of colony mass is majors, which may depress mean brood-rearing efficiency (Porter & Tschinkel, 1985). (vi) Larger colonies require longer lines of communication and resource distribution within the nest (Porter & Tschinkel, 1985). (vii) Clumping of brood in ants may reduce worker efficiency due to saturation of working space around the brood pile (Brian, 1956a; Porter & Tschinkel, 1985; but see Tschinkel, 2018). (viii) Costs of having to search a larger area for food supplies (Michener, 1964; Kramer *et al.*, 2014; Stroeymeyt *et al.*, 2017). (ix) Nest-site limitation (Kramer *et al.*, 2014; Stroeymeyt *et al.*, 2017). In many of these cases (but not all) the decrease in PCP the authors are trying to explain is based on incomplete measures of colony output and therefore is not necessarily a decrease in colony efficiency.

Equally important is to explain the numerous cases we report of neutral and positive effects on efficiency. Here we focus primarily on mechanisms likely to have a positive effect on efficiency, countering, at least in part, the negative effects listed above. We first consider potential gains in task-performance efficiency, followed by gains in task-integration efficiency.

(1) Task-performance gains

In a number of species of bees that form simple societies, groups as small as two benefit from efficiency gains (Tables 2 & 3) through the enabling of a rudimentary division

of labour (Schwarz, 1994; Schwarz *et al.*, 1998). Division of labour in guarding, nursing, and foraging can reduce handling and travelling times, reduce learning costs, and increase the amount of time that a guard is at the nest entrance, freeing up time for nestmates to spend foraging. With this most rudimentary form of division of labour, the total amount of effort devoted to foraging in a group of two can more than double, resulting in an increase in *per-capita* productivity (Packer, 1993). Because the variance of the mean decreases with increasing sample size, larger groups also benefit from a reduction of variance (= greater predictability) in food acquisition. In the literature, this simple statistical effect is sometimes referred to as the Central Limit Theorem (CLT) (Wenzel & Pickering, 1991; Stevens *et al.*, 2007). (Using proper statistical terminology, the CLT refers to asymptotic normality.)

Although the subset of studies with data available for our meta-analysis do not suggest a significant difference between Halictidae + Colletidae and the Xylocopinae in the DMA (Figs 11 & S3; $N = 45$), when the larger number of data sets reported in Tables 2 and 3 ($N = 86$) is considered, the difference in the proportion of positive, negative, and no-effect outcomes between the two groups implies significantly more negative effects in Halictidae + Colletidae ($\chi^2 = 7.74$, $df = 2$, $N = 86$, $P = 0.021$). This suggests that these two groups may differ in some aspect of their behaviour or ecology leading to lower *per-capita* efficiency in the Halictidae + Colletidae. Most studies of bees in these two groups use numbers of provisioned cells (Halictidae + Colletidae) or of immatures (Xylocopinae). Although body size is often variable in these bees (Michener, 1990a,b), making biomass a more precise measure of investment in output, the use of counts instead is not likely to account for the possible differences between the two taxa. One source of a potential difference may be reproductive conflict among founding females. Halictids set up dominance hierarchies in founding groups (Strohm & Bordon-Hauser, 2003; Kapheim *et al.*, 2013; Chole *et al.*, 2019), which may reduce *per-capita* output. This likely also explains the strong negative effect observed in the independent-founding Polistinae, which also exhibit overt conflict and dominance hierarchies. By contrast, agonistic interactions are less pronounced in the allodapines and do not appear to reduce ergonomic efficiency (Michener, 1990a; Schwarz *et al.*, 1998; Silva *et al.*, 2016). Further investigation is needed to determine if there is indeed a difference in efficiency between these groups, and if intra-colony conflict is responsible for it.

For several of the allodapines reported in Table 3, the gains in *per-capita* output peak at groups of two or a few females, then plateau or decline. Schwarz (1994) suggested that the positive effects for smaller groups trace to cooperative brood defence, increased task-performance efficiency, and lower *per-capita* costs in nest construction. With larger numbers, the negative effects of overcrowding in the hollow twigs or stems in which these bees nest may exceed the efficiency gains seen among smaller groups. That is, these two opposing selective forces may equalise at groups of 2–3.

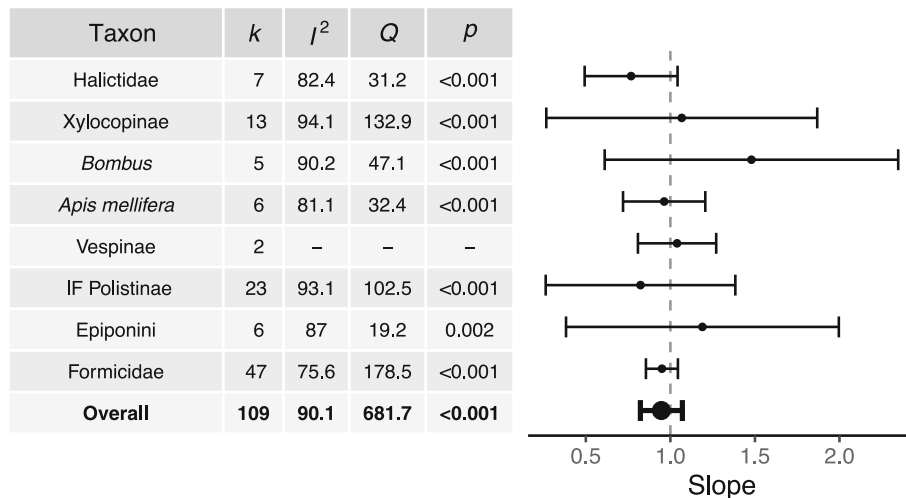


Fig. 10. Summary of results by taxonomic group for the continuous colony size meta-analysis (CMA). Effect sizes and 95% confidence intervals are plotted, with 1.0 indicating no effect of colony size on ergonomic efficiency. In the table, *k* is the number of data sets within each group, and results of *Q*-tests (*Q* statistics and *P* values) indicate whether there is significant residual heterogeneity in effect sizes, i.e. heterogeneity not due to sampling variance. *I*² values are a measure of the percentage of variance in the estimated slopes that is not due to sampling variance. For a full forest plot of all studies, see Fig. S1. IF Polistinae, independent-founding Polistinae.

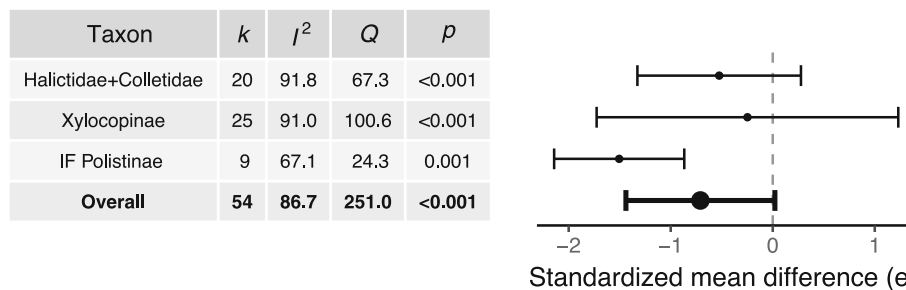


Fig. 11. Summary of results by taxonomic group for the discrete colony size meta-analysis (DMA). Effect sizes (standardized mean difference, *e*) and 95% confidence intervals are plotted, with 0 indicating no effect of colony size on *per-capita* productivity. In the table, *k* is the number of data sets within each group, *I*² values are a measure of the percentage of variance in the estimated slopes that is not due to sampling variance, and results of *Q*-tests (*Q* statistics and *P* values) indicate whether there is significant residual heterogeneity in effect sizes, i.e. heterogeneity not due to sampling variance. For a full forest plot of all studies, see Fig. S3. Note that broodless nests were omitted from this analysis. For results including broodless nests, see Fig. S4. IF Polistinae, independent-founding Polistinae.

With the larger colonies of *Bombus*, benefits arise from greater division of labour. *Bombus* is unusual among social Hymenoptera in its wide intraspecific range of worker body sizes, so it is not surprising that division of labour is tied more closely to worker size than to dominance interactions or age (Cameron, 1989). Larger workers tend to be foragers and guards, while smaller individuals tend to be brood nurses (Jandt & Dornhaus, 2009). For a number of *Bombus* species, foraging specialists have been shown to be more efficient at their tasks than are generalists (Cartar, 1992; Hagbery & Nieh, 2012). Large foragers forage at higher rates than small foragers (Spaethe & Weidenmüller, 2002). Flower constancy by foragers leads to increased speed of flower handling and faster transitions between flowers (Chittka & Thomson, 1997).

Foragers attain their best performance when they have learned only one flower species and specialize on it: they make fewer errors, are faster at correcting them, and have the lowest handling times (Heinrich, 1976; Chittka & Thomson, 1997). Several studies show that speed of accessing pollen and nectar in morphologically complex flowers increases with experience (Laverty, 1980; Laverty & Plowright, 1988; Raine & Chittka, 2007; Muth, Papaj & Leonard, 2016), suggesting that this effect will be larger in larger colonies, where the degree of specialization can be greater. Inside the nest, workers tend to remain within small spatial zones, which can lead to efficiency gains by minimizing the distance they travel between tasks (Jandt & Dornhaus, 2009). Worker body mass within a colony can range over an order of magnitude in some *Bombus* species

(Goulson *et al.*, 2002), suggesting that if the range increases later in the colony cycle, it would enable more efficient division of labour in larger colonies (Plowright & Jay, 1968). However, a test on one species (*B. impatiens* Cresson) showed that the range and variance in worker size actually decreased with colony size (Couvillon *et al.*, 2010), casting doubt on this hypothesis. Colony performance in thermoregulation and undertaking behaviour did not increase with variation in worker body size (Jandt & Dornhaus, 2014). A direct test using *B. impatiens* showed that colony performance, but not degree of variation in size, increases with mean worker size (Herrmann, Haddad & Levey, 2018). If production costs and lifespan are taken into account, intermediate-sized workers were shown to have the highest net resource contribution (Kerr, Crone & Williams, 2019). The question of how natural selection maintains size polymorphism in *Bombus* workers remains unresolved.

The much larger colony sizes found in many species in the three more socially complex taxa – the swarm-founding bees (*Apis*) and wasps (Epiponini) and some ants – create opportunities for additional mechanisms that increase task-performance efficiency (Richards & Richards, 1951; Bourke & Franks, 1995). Some of the examples of the effects of colony size in the following discussion cite interspecific differences, but the principles apply intraspecifically as well. Large colonies are characterized by decentralized worker control under which workers play a pure helper strategy (Bourke, 1999; Jeanne, 2003), creating opportunities for efficiency gains that selection at the colony level should favour. The underlying enabling mechanism is the well-documented increase in division of labour that emerges in larger colonies (Gautrais *et al.*, 2002; Thomas & Elgar, 2003; Jeanson *et al.*, 2007; Holbrook, Barden & Fewell, 2011; Ferguson-Gow *et al.*, 2014; Fewell & Harrison, 2016; Ulrich *et al.*, 2018). Temporal (age) polyethism, widespread in all three groups, typically allocates risky tasks to older individuals, providing a demographic advantage (Seeley, 1982; Jeanne, 1986a; Wakano, Nakata & Yamamura, 1998; Tofilski, 2002, 2006). The resulting increase in specialization gives rise to a variety of mechanisms that can increase task-performance efficiency in individual workers. Specialist foragers forage farther, spend more time in the field than non-specialists (Thomas & Framenau, 2005), forage at higher rates (O'Donnell & Jeanne, 1990), carry larger loads (Eckert, 1990; Wolf & Schmid-Hempel, 1990), and spend less time resting (Smith, Koenig & Peters, 2017), although exceptions have been reported (e.g. Fewell, Ydenberg & Winston, 1991; Dornhaus, 2008). The rate of foraging success increases with experience in some social wasps (Akre *et al.*, 1976; O'Donnell & Jeanne, 1992), but not in others (Santoro, Hartley & Lester, 2019). Among nest workers, specialization on one or a few tasks leads to reduced delays in the search for new tasks, reduced response thresholds for performing those tasks, and faster and more error-free task completion (Trumbo & Robinson, 1997; Weidenmuller, 2004), resulting in lower rates of task switching by individuals and more tasks performed per worker (Thomas & Elgar, 2003;

Holbrook *et al.*, 2013). An increase in group size in small artificial colonies of the clonal raider ant, *Ooceraea biroi* (Forel), can increase colony homeostasis by stabilizing task performance frequencies and decreasing task neglect, and this effect may operate independently of the increase in division of labour, which also improves homeostasis and colony growth (Ulrich *et al.*, 2018). Modelling has shown that the cost of task switching can select for division of labour (Goldsby *et al.*, 2012), although in the clonal raider ant, experiments and modelling suggest that reduced task switching can emerge in larger groups even in the absence of a cost (Ulrich *et al.*, 2018). In ants with polymorphic workers, each size-based subcaste is most efficient at performing the tasks it specializes on (Wilson, 1980; Porter & Tschinkel, 1985; Kay & Rissing, 2005; Tschinkel, 2006; Mertl & Traniello, 2009). Elites – workers that consistently perform disproportionately more work than others – are widespread in these groups (Oster & Wilson, 1978; Hurd, 2005; Pinter-Wollman *et al.*, 2012; Modlmeier *et al.*, 2014; Hammel *et al.*, 2016; Mateus *et al.*, 2019). Finally, individuals vary in their degree of flexibility of task performance: more canalized workers gain efficiency through greater specialization and a reduction in the cost of task switching, whereas more flexible individuals may allow colonies to adapt more rapidly to environmental fluctuations (Jeanson, 2019). Whether the balance between flexible and canalized individuals responds in an adaptive way to changes in colony size or stage of development remains to be investigated (Jeanson, 2019).

(2) Task-integration gains

In the simple social bee taxa, there is little evidence that task-integration efficiency increases with colony size. Task partitioning – the division of materials-handling tasks into subtasks, each carried out by specialists (Jeanne, 1986a) – does not occur. Even in large *Bombus* colonies, returning pollen and nectar foragers deposit their loads directly into storage pots (Michener, 1974). This suggests that the observed increase in *per-capita* productivity with colony size in *Bombus* colonies derives primarily from gains in task-performance efficiency. On the other hand, the efficiency of their nest-based food-alert system (Dornhaus & Chittka, 2001; Dornhaus, Brockmann & Chittka, 2003) likely increases with colony size.

In the complex social groups – ants and swarm-founding bees and wasps – increases in task-performance efficiency through specialization among workers are accompanied by increases in task-integration efficiencies. Larger colonies tend to have more sophisticated forms of communication (Beckers *et al.*, 1989; Beekman, Sumpter & Ratnieks, 2001), with efficiency gains coming through the expanded use of cues and signals, more rapid transfer of information, reduced queuing delays for material transfer, and Allee effects (Oster & Wilson, 1978; Jeanne, 1986b, 1999, 2003; Hölldobler & Wilson, 1990; Wilson, 1990; Queller, 1996; Anderson & Ratnieks, 1999; Mailleux, Deneubourg & Detrain, 2003; Tschinkel, 2006; O'Donnell & Bulova, 2007; Johnson, 2010; Luque, Giraud & Courchamp, 2013) and greater resilience in the face of stochastic events (Fewell & Harrison, 2016).

Series-parallel processing and the greater redundancy in larger groups lead to greater reliability at the colony level (Oster & Wilson, 1978), even if individual reliability declines (Herbers, 1981). Larger colonies also generate greater rates of encounters among nestmates (Karsai & Wenzel, 1998; Smith *et al.*, 2017). The resulting enhanced connectivity among workers (O'Donnell & Bulova, 2007) leads to greater information-gathering capacity (Donaldson-Matasci, DeGrandi-Hoffman & Dornhaus, 2013) and enhanced information flow within the colony (Gordon, 1996; Pacala, Gordon & Godfray, 1996; Hollbrook *et al.*, 2013).

The recognition that reporting the mean behaviour of individuals belonging to temporal or physical castes is not fine-grained enough fully to explain colony dynamics has given rise to the concept of 'key individuals', workers that enhance task-integration efficiency by facilitating colony activities. Drawing on their work with ants, Robson & Traniello (1999) proposed three functional categories of key individuals: *catalysts* stimulate others to greater activity, *performers* carry out the majority of work but do not motivate others to assist, and *organizers* maintain group cohesion around a task until it is completed, but do not take part in the task. Others have identified different categories of key individuals that are specific to particular species (e.g. Frank & Linsenmair, 2017).

As colonies grow in size, more complex ways of organizing work emerge that may enhance efficiency (Gautrais *et al.*, 2002). Task partitioning is a common form of emergent behaviour in larger colonies. In many species of bees, wasps, and ants, foragers hand off their loads to nest workers who then distribute the materials to the larvae, food-storage areas, or to workers engaged in nest construction. This introduces a cost in the form of a finite queuing delay in the transfer of the material, but modelling shows that this cost decreases roughly exponentially as colony size increases (Anderson & Ratnieks, 1999). Complete task partitioning enables more efficient workflow in larger colonies (Anderson & Ratnieks, 1999). At least in some cases, points of no return can be passed. As an example, on one extremely small pre-emergence colony of the swarm-founding wasp *Polybia occidentalis* (14 females; nest under construction with 66 cells, no envelope) in Costa Rica, the pulp and water foragers continued to return with full loads, much bigger than builders could work with, leading to extremely long queuing delays in transferring their materials to receivers at the nest (Jeanne, 2003). For colonies this small it probably would be more efficient to abandon the series-parallel system that task partitioning engenders and fall back on the parallel-series system of the independent-founding wasps, but the species apparently lacks the behavioural flexibility to do so, resulting in a loss in efficiency for small colonies of this species (Jeanne, 2003).

Even more complex forms of cooperation occur in some ants. Retrieval of solid food by groups or teams of workers, documented in over 40 genera (Hölldobler & Wilson, 1990), increases the size range of food items a colony can exploit (Czaczkes & Ratnieks, 2013; McCreery & Breed, 2014), but requires a high degree of coordination among the workers. Efficiency gains come in several ways. The speed of transport, for example, increases with the

number of ants carrying an item (Czaczkes, Nouvellet & Ratnieks, 2011). In the swarm-raiding army ants, prey-retrieval teams can be 'superefficient', able to carry more as a single piece than the same number of workers could carry if the piece were fragmented and divided among them (Franks, 1986; Anderson & Franks, 2001).

Finer degrees of task partitioning occur in some of the seed-harvester and leaf-cutting ants. Bucket-brigading is a multi-stage partitioned foraging system consisting of direct load transfer between individual workers (Anderson & Jadin, 2001; Anderson, Boomsma & Bartholdi, 2002). A leaf forager (*Atta* sp.) carries her load along the trunk trail towards the nest until she meets an unladen outgoing ant. If the load is transferred, each worker reverses direction. A given leaf fragment can experience more than one such transfer on its way to the nest. The seed-harvesting ant *Messor barbarus* (Linnaeus) uses a similar system. Efficiency gains may come through foragers becoming faster at traversing the section of trail they are most familiar with. Transfers tend to be in the direction of larger, faster workers, resulting in higher mean transport rates to the nest and an increase in efficiency (Reyes & Fernández-Haeger, 1999; Anderson *et al.*, 2002).

An even more extreme form of partitioning in *Atta* involves indirect transfer of leaf fragments *via* caches (Fowler & Robinson, 1979). In many populations, each forager ascends a tree, cuts a leaf fragment, and carries it down the tree and on to the nest, perhaps with transfers along the way. But in others, colonies deploy a small number of smaller workers into the tree canopy to cut large pieces of leaf and let them drop to the ground. On the ground, a second group cuts the fallen leaves into portable fragments, carries them to the nearest trunk trail, and drops them in a pile. A third group exploits these caches and transports the pieces to the nest. This is a particularly good example of economy of scale. The cut-and-drop system is more efficient than cut-and-carry when the ratio of fragments that reach the nest to those that do not is more than the ratio of the cost of cutting and dropping a fragment to that of climbing and descending the tree (Hubbell *et al.*, 1980). In the Fowler & Robinson (1979) study, the former ratio was 1:1, that is, about 50% of cut and dropped fragments were recovered. Although the energetic costs have not been quantified, it is likely that the smaller the colony the smaller the recovery ratio, so that cut-and-drop becomes the more efficient strategy only when the colony reaches a certain size threshold, although this remains to be tested.

Empirical support linking any of these performance- and integration-enhancing mechanisms to greater *per-capita* output at the colony level in larger colonies is sparse. One study compared the efficiency of nest-construction behaviour in large and small colonies of the wasp *Polybia occidentalis* (Jeanne, 1986b). Large colonies (mean size: 512 adults) accomplished a standardized amount of nest-construction labour in just 57% of the time required by small colonies (mean of 32 adults) to do the same amount of work. Most of the time saved came in the form of shorter queuing delays

during transfer of materials from one worker to another at the nest. Workers in large colonies spent 45% less time at these tasks than in small colonies, compared to an 11% saving for water and wood-pulp foraging, tasks that involve no transfers. In other words, much more of the increase in efficiency seen in large colonies was due to gains in task-integration efficiency than task-performance efficiency. This increase in task-integration efficiency aligns with colony-level results showing that larger colonies are as or more productive *per capita* (Jeanne, 1986b) and rear brood significantly faster (Howard & Jeanne, 2004) than smaller ones. It remains to be determined how much of these colony-level efficiency gains are the result of the increased ergonomic efficiency documented at the individual level. Additional benefits of larger colonies may come from the greater predictability of resource acquisition (Wenzel & Pickering, 1991) and to more effective thermoregulation of the nest (Howard & Jeanne, 2004). The relative importance of these and perhaps other yet-unrecognized benefits of larger size remains to be investigated.

Only a few studies have documented organizational transitions in response to ontological increases in colony size. When colonies of *Monomorium pharaonis* (Linnaeus) grow to 600–700 workers they undergo a non-linear phase shift from disorganized foraging (no trail pheromone) to organized (pheromone-trail-based) foraging (Beekman *et al.*, 2001). Colonies of the desert leafcutter ant (*Acromyrmex versicolor*) undergo a similar phase transition in efficiency during early colony development (Clark & Fewell, 2014). In the yellowjackets *Vespula pensylvanica* (de Saussure) and *V. atropilosa* (Sladen), foraging for nectar and prey and their distribution at the nest are rarely partitioned in small (young) colonies, but partitioning becomes the rule later in development, when colonies are larger and queuing delays are short (Akre *et al.*, 1976). In several ant species the degree of partitioning of honeydew collection from aphids increases with colony size (Novgorodova, 2015). When colonies of *Formica cunicularia* Latreille are small (10^2 workers), each forager engages in sequential collection and transport to the nest; when colonies reach 10^3 , foragers specialize as either ‘shepherds’ (collect honeydew), ‘guards’ (protect aphids from competitors), or ‘scouts’ (search for new aphid colonies). When colonies of *F. lugubris* Zetterstedt grow to 10^5 workers, they add specialized transporters, or tank-truckers, that collect honeydew from shepherds and bring it to the nest. This increasing degree of specialization as colonies grow likely increases the efficiency of honeydew harvesting.

Such facultative responses to growth in colony size are probably especially adaptive for haplometrotic species, such as yellowjacket wasps and many ants, whose colonies are initiated by a single queen and undergo growth in their worker populations to thousands, millions, or more. For swarm-founding species, the relative increase in size from the founding group to mature colony size is much less, so such flexibility may be less adaptive.

Among the questions remaining to be investigated is whether simpler forms of task organization, such as the

parallel–series system of foraging for nectar and prey seen in small colonies of *Vespula*, for example, are replaced by a task-partitioned series–parallel system because they become *less* efficient as colony size grows or because the series–parallel system becomes *more* efficient, even if the efficiency of the former does not change.

VIII. CONCLUSIONS

- (1) Michener speculated that one of the causes of the declining *per-capita* output he reported is that workers become less efficient as colony size increases (Michener, 1964). This has wrongly come to be accepted as supported by Michener’s analyses. If this were true, then natural selection should (in the absence of survival benefits to large colonies) favour the evolution of ever-smaller colony size, ultimately leading to solitary behaviour. That sociality persists in the face of this has been called ‘Michener’s paradox’ (Wenzel & Pickering, 1991). By defining efficiency correctly and treating its claimed negative relationship to colony size as a hypothesis to be tested, we have shown that for many taxa the hypothesis has little support. We argue instead that the pattern Michener reported can be traced to his use of proxies for *per-capita* output of sexuals, allowing a variety of biasing factors not related to ergonomic efficiency to go unaccounted for. These include intrinsic factors (e.g. limits of queen fecundity; allocation of investment in mature colonies to forms of output not captured by the proxies), extrinsic factors (e.g. seasonal differences in resource availability), and methodological errors (e.g. failure to measure all forms of colony output; inappropriate experimental design). In many cases, if these causes of decreasing *per-capita* productivity are controlled for and if all forms of worker output are taken into account, overall efficiency does not decrease and Michener’s so-called paradox disappears. We conclude that most studies fail to support the hypothesis: in many species, larger colonies frequently show no decline, or even an increase, in output *per capita* compared to smaller ones. In a review of 215 data sets in our systematized review and 163 data sets in the meta-analyses, we find support for the Michener pattern only in the independent-founding paper wasps and possibly the halictid bees. Factors other than ergonomic efficiency, both extrinsic and intrinsic, can of course interact with colony size, both as cause and as effect. Their effects, however, are anything but paradoxical and can be parsed and measured by carefully designed observations and experiments.
- (2) Only if *per-capita* productivity includes all forms of input and output does it measure a colony’s efficiency. Because most published studies use proxy measures of input and/or output, i.e. measure only one form of input and/or output, their measures of *per-capita*

productivity are not valid measures of efficiency. In most of the studies Michener analysed, reproductivity in terms of numbers of reproductives produced is not what was measured. In his case studies, small colonies often showed a higher *per-capita* output than did large ones simply because more of their total effort went into what the proxy measured than was the case for larger colonies. Despite these shortcomings, studies using proxies are useful for the more limited purpose of assessing the effects of colony size on PCP within a sample of colonies of a species, as long as biasing variables such as colony stage, season, and others are strictly controlled for.

- (3) Because few of the studies reviewed here had the measurement of *per-capita* productivity as their primary purpose, we cannot conclude that the hypothesis that ergonomic efficiency decreases in larger groups has been fully tested and fails. That will require additional studies designed specifically to measure ergonomic efficiency in targeted taxa, with the proper phylogenetic corrections in place. But at a minimum, the results of our survey call the hypothesis into serious question for many species. This is not to deny that the paradox can occur in principle. The halictids (Table 2) may be good candidates. If colony efficiency actually does decline with group size in some species, then the mechanisms behind it can be sought. We have suggested reproductive conflict among founding females as one mechanism. In addition, perhaps in these groups workers actually do get in one another's way, as Michener speculated.
- (4) Although the focus of Michener's analysis and of this review is on colony dynamics at the intraspecific level, the question of the relationship between colony size and colony efficiency can be posed across species as well. Do large-colony species in genera such as *Atta*, *Apis*, and *Agelais* convert resources into reproductives more (or less) efficiently than do small-colony species in such genera as *Leptothorax*, *Megalopta*, and *Mischocyttarus*?
- (5) At the interspecific level, it is clear that the various major taxa of eusocial Hymenoptera are characterized by differing degrees of division of labour and task partitioning. Stingless bees and honey bees partition nectar-handling tasks (Seeley, 1995; Hart & Ratnieks, 2002), but bumble bees do not (Michener, 1974). Among the social wasps, *Polistes* and other independent-founding polistines have very weak temporal polyethism and rudimentary task partitioning (Jeanne, 1999), whereas the epiponine wasps have strong temporal polyethism and complete task partitioning of the handling of all resources (prey, nectar, water, and nesting material) (Jeanne, 1986b). The vespines appear to be intermediate between the independent- and swarm-founders. Despite colonies that can grow to thousands of workers, they have weak temporal polyethism and partition the handling of food but not of nest material.
- (6) In sum, efficiency gains in larger groups, both within and across species, can accrue through a combination

of economies of scale and more efficient performance and organization of tasks, including division of labour, worker specialization, greater task integration, group food retrieval, and task partitioning (Traniello & Beshers, 1991; Shakarad & Gadagkar, 1995; Anderson & Ratnieks, 1999; Anderson *et al.*, 2002). The range of colony sizes over which each of these will become cost-effective likely varies widely from one type of benefit to another. For example, the simple partitioning of resource-handling tasks into foraging by one group of workers and distribution/utilization on the nest by another may become cost effective at colony sizes of a hundred workers or fewer, whereas leaf dropping and caching by attine ants may require colonies of hundreds of thousands for it to realize efficiency gains, but then the gains may be substantial.

- (7) Ergonomic efficiency, a measure of how cost effectively a colony converts resources into reproductives, is a social trait and a component of colony fitness. It is a colony-level phenotype through which natural selection acts not only on colony size, but on such work-organizational traits as division of labour, task partitioning, and mechanisms of colony integration *via* cues and signals (Holbrook *et al.*, 2011; Goldsby *et al.*, 2012). It could be argued that this is the mechanism through which 'emergent behaviour' emerges in social insect colonies. Natural selection should act at the colony level to increase efficiency, and probably acts most strongly when colonies are larger and potential energetic savings are greater. An unresolved, but possibly important issue is the causal relationship between efficiency, size, and colony failure: can low efficiency be a cause of colony failure in small colonies of any species?
- (8) Because of the scientific community's failure to interpret Michener's paper correctly, we have barely begun to investigate the cause-effect relationships between colony size and colony efficiency. A full understanding of the evolution and maintenance of colony size will require clarity about how these traits interact and respond to selection. Does enhanced efficiency enable larger colony size, or does cause-effect work in the other direction? Thus, the role of energetic efficiency is deserving of study (Fjerdingstad & Crozier, 2006; Modlmeier & Foitzik, 2011), not just in social insects, but in any group of cooperating individuals, including humans and robots.

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XI. Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Fig. S1. Full forest plot for the continuous colony size meta-analysis (CMA).

Fig. S2. Phylogenetic trees used to control for shared ancestry in the continuous meta-analysis and the discrete meta-analysis.

Fig. S3. Full forest plot for the discrete colony size meta-analysis (DMA).

Fig. S4. Full forest plot for the discrete colony size meta-analysis (DMA), including broodless colonies.

Table S1. Details of the data sets used in the continuous colony size meta-analysis (CMA).

Table S2. Details of the data sets used in the discrete colony size meta-analysis (DMA).

Table S3. Multivariate meta-analysis model results for the continuous colony size meta-analysis (CMA).

Table S4. Multivariate meta-analysis model results for the continuous colony size meta-analysis (CMA) with taxonomic and output moderators.

Table S5. Multivariate meta-analysis model results for the offspring mass data sets in the continuous colony size meta-analysis (CMA).

Table S6. Multivariate meta-analysis model results for the complete-output data sets in the continuous colony size meta-analysis (CMA).

Table S7. Multivariate meta-analysis model results for the large-colony taxa in the continuous colony size meta-analysis (CMA).

Table S8. Multivariate meta-analysis model results for the large-colony taxa in the continuous colony size meta-analysis (CMA) with taxonomic and output moderators.

Table S9. Multivariate meta-analysis model results for the discrete colony size meta-analysis (DMA).

Table S10. Multivariate meta-analysis model results for the discrete colony size meta-analysis (DMA) with taxonomic moderators.

Table S11. Multivariate meta-analysis model results for the discrete colony size meta-analysis (DMA), including broodless nests in studies that reported them.

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