REVIEW / SYNTHÈSE

The status of taxonomy in Canada and the impact of DNA barcoding[1]

L. Packer, J.C. Grixti, R.E. Roughley, and R. Hanner

Abstract: To assess the recent history of taxonomy in Canada and the impact of DNA barcoding upon the field, we performed a survey of various indicators of taxonomic research over the past 30 years and also assessed the current direct impact of funds made available for taxonomy through the DNA barcoding NSERC (Natural Sciences and Engineering Research Council of Canada) network grant. Based on results from surveys of three Canadian journals, we find that between 1980 and 2000 there was a 74% decline in the number of new species described and a 70% reduction in the number of revisionary studies published by researchers based in Canada, but there was no similar decline for non-Canadian-authored research in the same journals. Between 1991 and 2007 there was a 55% decline in the total amount of inflation-corrected funds spent upon taxonomic research by NSERC's GSC18 (Grant Selection Committee 18); this was a result of both a decrease in the number of funded taxonomists and a decrease in mean grant size. Similarly, by 2000, the number of entomologists employed at the Canadian National Collection (CNC) had decreased to almost half their 1980 complement. There was also a significant reduction in the number of active arthropod taxonomists in universities across the country between 1989 and 1996. If these declines had continued unabated, it seems possible that taxonomy would have ceased to exist in Canada by the year 2020. While slight increases in personnel have occurred recently at the CNC, the decline in financial assistance for taxonomists has been largely reversed through funds associated with DNA barcoding. These moneys have increased the financial resources available for taxonomy overall to somewhere close to NSERC's 1980 expenditures and have also substantially increased the number of HQP (highly qualified personnel) currently being trained in taxonomy. We conclude that the criticism "DNA barcoding has taken funds away from traditional approaches to taxonomy" is false and that, in Canada at least, the advent of DNA barcoding has reversed the dramatic decline in taxonomy. We provide recommendations on how to foster the future health of taxonomy in Canada.

Résumé : Afin d'évaluer l'évolution récente de la taxonomie au Canada et l'impact de l'utilisation des codes à barres ADN sur la discipline, nous avons fait l'inventaire de divers indicateurs de la recherche taxonomique au cours des 30 dernières années; nous avons aussi évalué l'impact direct actuel des fonds mis à la disposition de la taxonomie par la subvention de réseau de codage par codes à barres du CRSNG (Conseil de recherches en sciences naturelles et en génie du Canada). D'après les résultats des inventaires faits dans trois revues canadiennes entre 1980 et 2000, il y a eu un déclin de 74 % du nombre de nouvelles espèces décrites et une réduction de 70 % du nombre de travaux de révision publiés par des chercheurs basés au Canada, mais aucune réduction similaire des travaux de recherche provenant d'auteurs non canadiens dans les mêmes revues. Entre 1991 et 2007, il y a eu un déclin de 55 % dans la quantité totale de fonds, après correction pour l'inflation, consacrés à la recherche taxonomique par le comité CSS18 (Comités de sélection des subventions 18) du CRSNG; c'est le résultat à la fois d'une diminution du nombre de taxonomistes subventionnés et une réduction de la subvention moyenne. De même, en 2000, le nombre d'entomologistes à l'emploi de la Collection nationale du Canada (CNC) avait diminué de moitié par rapport à l'accompagnement dans les années 1980 et il y avait une réduction significative du nombre de taxonomistes des arthropodes actifs dans les universités dans tout le pays entre 1989 et 1996. Si ces déclins s'étaient poursuivis sans remède, il apparaît possible que la taxonomie ait cessé d'exister au Canada avant l'année 2020. Alors qu'il y a eu récemment une faible augmentation du personnel à la CNC, le déclin de l'aide financière aux taxono-

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mistes a été en grande partie contrecarré par les ressources financières associées au codage par codes à barres. Ces argents ont augmenté les ressources financières disponibles à la taxonomie globalement à un niveau assez proche des ressources dépensées par le CRSNG en 1980 et ont accru la quantité de personnes hautement qualifiées (HQP) actuellement en formation en taxonomie. Nous concluons que la critique qui veut que le codage par codes à barres ADN ait retiré des fonds aux approches traditionnelles de la taxonomie est fausse et qu'au Canada au moins, l'arrivée du codage par codes à barres ADN a renversé la tendance au déclin de la taxonomie. Nous présentons des recommandations pour améliorer la santé future de la taxonomie au Canada.

[Traduit par la Rédaction]

Introduction

Taxonomy is fundamental to all of biology, yet there have been numerous reports that the state of the discipline is in decline worldwide (e.g., Winston and Metzger 1998; Disney 2000; Lee 2000; Herbert et al. 2001; Kim and Byrne 2006). This apparently dismal state of affairs is surprising considering the crucial role that taxonomy plays in many aspects of the human enterprise (House of Lords 1992, 2002, 2008; Australian Academy of Science 1996; Hoagland 1996; McFadyen 1998; Guarro et al. 1999; Giangrande 2003; Meyerson and Reaser 2003; Valdecasas and Camacho 2003; Isbister et al. 2004; Mace 2004; Roughley 2005; National Research Council 2006; National Science and Technology Council 2009). That this taxonomic impediment applies to such comparatively well-investigated organisms as mammals (Brito 2004) may come as a surprise to those who are not practicing taxonomists.

That the biodiversity crisis extends to a loss in the taxonomic knowledge base in terms of personnel capable of the recognition and description of life's diversity has been recognized for some time (Wilson 2000; Hopkins and Freckleton 2002). This has led to some attempts at mitigation (House of Lords 1992, 2002, 2008; Rodman and Cody 2003; Agnarsson and Kuntner 2007). In Canada, the problem of a decline in taxonomic capacity was recognized (Efford 1995) and $320 000 was specifically allocated for taxonomic research by the Natural Sciences and Engineering Research Council of Canada (NSERC) in 1998. This infusion was temporary and has not been repeated, although a few stipends of $5 000 have been made available for graduate students who were working in close collaboration with museum-based taxonomists.

The purpose of this paper is to assess the recent state of taxonomy in Canada and to assess the influence that DNA barcoding may be having upon it.

Since its inception in 2003 (Hebert et al. 2003), DNA barcoding has elicited a wide range of responses, from enthusiastic endorsement (Schindel and Miller 2005) to absurd caricature (Rubinoff et al. 2006). The criticisms have been wide ranging, from claims its full application would be damaging to children (Larson 2007) or that it simply does not work (Rubinoff et al. 2006) to the view that it is taking funding away from traditional taxonomic approaches (e.g., Löbl and Leschen 2005; Rubinoff et al. 2006). In this paper, we address the last complaint in detail through analysis of a large number of variables associated with Canada's taxonomic capacity from 25 years before the advent of DNA barcoding up to the present (for treatment of most of the other criticisms of DNA barcoding see Packer et al. 2009).

It is important at the outset for us to differentiate between two related terms, "taxonomy" and "systematics". Taxonomy is most commonly considered to be the science of describing biological diversity (Wilson 1985; Quicke 1993; Winston 1999; but see Ball 1981; Wheeler 1990), while systematics is the study of relationships among taxa (or some attributes thereof) within a phylogenetic context. Thus, we consider taxonomy to be a component of systematics. Thus defined, taxonomic research of good quality should always contribute towards our ability to identify organisms correctly, whereas systematic research, irrespective of its quality, may not always do so and may often be an impediment (Wilson 2000; Landrum 2001; Q.D. Wheeler 2004; T.A. Wheeler 2004).

The main goal of DNA barcoding is to provide accurate species-level identifications. It is clearly successful in doing this using just the standard barcode region of the *COI* gene for most animals (corals are an exception). In particular, when one compares the accuracy of DNA barcoding to that of traditional approaches to taxonomy, DNA barcoding is generally far superior and clearly outperforms morphology in analysis of difficult species complexes (Sheffield and Westby 2007; Gibbs 2009*a*, 2009*b*; Packer et al. 2009), as well as in associating larval and adult forms (Miller et al. 2005).

Materials and methods

The status of taxonomic research in Canada

We assessed Canada's capacity for and productivity in taxonomic research in as diverse a number of ways as possible with data available to us. Below we first assess research output in terms of publications and other measures of taxonomic productivity. We then assess the number of people employed as trainees and as career professionals in entomological taxonomy in Canada. We also use data from NSERC to assess the amount of funds expended upon researchers who perform taxonomic work and training in Canada. Lastly, we present data on research funds and training of "highly qualified personnel" (HQP) in taxonomic areas that are resulting directly from funds for DNA barcoding.

Publication data

We surveyed the three leading Canadian journals expected to be the vehicles for publishing most taxonomic research in the country: *Canadian Journal of Zoology* (henceforth CJZ), *Canadian Journal of Botany* (currently known as *Botany*) (CJB), and *The Canadian Entomologist* (TCE). We surveyed these journals for three time periods of 3 years each: 1978–1980, 1988–1990, and 1998–2000. For brevity these categories are referred to as the 1980, 1990, and 2000 time periods, or more simply 1980, 1990, and 2000. This sampling intensity provided sufficient data for most of our analyses, whereas single year sampling would have been less trustworthy through, for example, unduly increasing the impact of single papers that described an unusually large number of new species. For some analyses we also used similar data from three additional Canadian publication sources: *Quaestiones Entomologicae*, *Memoirs of the Entomological Society of Canada*, and the National Research Council Monograph Series. The great increase in potential outputs of taxonomic research in recent years makes a similar analysis for current research productivity almost impossible. Instead, to assess the impact of DNA barcoding upon taxonomic research output, we asked recipients of barcoding funds to answer a questionnaire (see below).

Data on taxonomy-related research was summarized for each journal and time period. For each time period we counted the number of published articles that had one or more species description, the number of new species described, the number of articles that were taxonomic irrespective of whether they included new species descriptions, the number of articles that were more broadly systematic in nature, and to control for variation in research productivity overall, also the total number of research articles on any subject published. The description of new higher level taxa was much less common, but data on this were also collected. These data were broken down into Canadian-based researcher (CbR) and non-Canadian-based researcher (nCbR) authorship categories. A multi-authored paper was placed in the former category if the senior author was from a Canadian institution. Patterns in the relative contribution of Canadian research to the journal's taxonomic publications over time could be evaluated in terms of the change in numbers for CbR versus that by nCbR. Thus, the publication rate in taxonomy from nCbR served, to some extent, as a control against which to assess variation in the taxonomic productivity of CbR. For Canadian authors we differentiated between university-based and government-based scientists.

The above refers to the quantity of taxonomic research, but what of its quality? This is very difficult to assess for numerous reasons, for example, none of the authors of this paper are well qualified to evaluate the quality of work in botanical or non-entomological and non-ichthyological aspects of animal taxonomy. We used several variables as proxies for the quality of taxonomic research work: the proportion that included an identification key and the frequency of taxonomic revisions. We considered the number of papers that were full-scale revisions of particular taxa, or geographically delimited portions of an entire higher level taxon (species group or above), to be particularly important examples of taxonomic work. We did not include in this category papers that did not either describe or redescribe all of the species included in the group (except in the rare instances when a few species were unavailable for study). We also assessed the proportion of studies that included a phylogenetic analysis.

Personnel data

We collected data on the number of personnel performing systematic–taxonomic research in Canada in two ways. First, we counted the number of people employed in systematic entomological and arachnological research at the Canadian National Collection (CNC) in Ottawa (Dang 1992; Huber and Cumming 1999; J.M. Cumming, personal communication). Second, we used two published lists of workers in systematic and related research on "insects and certain related groups" in Canada (Danks and Ridewood 1989; Danks and Goods 1997). These lists were compiled from responses to questionnaires and may suffer from the usual difficulties associated with information that is volunteered. Nonetheless, there is no reason to believe that such shortcomings affected data from the two questionnaires differentially. These data do not correspond exactly to the time periods relating to research output. Nonetheless, changes in responses to the questionnaires should reflect changes in the state of taxonomy in Canada over the time period surveyed.

From Danks and Ridewood (1989) and Danks and Goods (1997) we included as taxonomists those respondents who chose taxonomy as one of their major fields of research interest. We subdivided taxonomists based on whether they were University professors, graduate students (including postdoctoral fellows — only one in each survey), research assistants, researchers at CNC, researchers at other branches of national or provincial governments, consultants, retirees, or amateurs. Those listed as "independent researchers" were grouped together with those responding that they were amateurs. University professors whose interest in taxonomy involved groups that they were not "officially" researchers of (such as mammalogists who studied Lepidoptera as a hobby) were included as amateurs. We included in our data only individuals who provided Canadian addresses in their questionnaire responses.

Funding data

We obtained funding data from NSERC using the awards search engine on their Web site (http://www.outil.ost.uqam.ca/CRSNG/Outil.aspx?Langue=Anglais). An initial search was restricted to Grant Selection Committee 18 (GSC18), Evolution and Ecology, because this is the committee that has funded the great majority of taxonomic research. We included both individual and group discovery grants in our search. We included as data all personnel receiving funds in the years 1991–1992 (the earliest available in the database), 2000–2001, and 2007–2008 (the most recent). Note that our data include all research fund recipients, not only those receiving grants as a result of competitions in that year.

Based upon grant titles and knowledge of the field, researchers were grouped into those that were likely to perform standard morphology-based taxonomic research on living organisms as part of their own research program and those that did all other forms of research. We did not include molecular systematists in the former category unless they combined molecular and morphological approaches in their research program. We also did not include taxonomists working on fossils in our taxonomist category simply because DNA barcoding is not (yet?) readily applicable to such work and because palaeontology is not of broad application to the identification of extant taxa.

A second search was based upon research subject codes, where "taxonomy, systematic and phylogenetics" is an option. This was performed across all grant selection committees. This search yielded a total of seven additional grants in taxonomy that were awarded through GSCs other than GSC18 (six in 1991 and one in 2000) and provided a check for taxonomic grants awarded through GSC18 that our initial searches may have missed. For statistical comparisons between taxonomist and non-taxonomist grant funds, we did not include the seven non-GSC18 data points because we did not analyse non-taxonomic research among other GSCs. However, we did include these seven grants in summary statistics such as the total amount of funds available for taxonomic research in any given time period.

In all cases where we were not certain whether an individual grantee was involved in traditional taxonomic research, we performed a Google Scholar search under their name and (or) searched their university Web site and assessed the kind of work they published.

To correct grant amounts for inflationary pressures, we obtained data on the relative purchasing power of the Canadian dollar over the time periods under discussion (Bank of Canada 2009).

We also had access to information on expenditures from the barcoding grant to researchers who perform empirical taxonomic research (as opposed to other areas supported by the network, such as informatics and molecular technologies). These were obtained through the network director with additional data coming from our questionnaire (see below).

The impact of DNA barcoding upon taxonomic research in Canada

For a variety of reasons, a direct assessment of the impact of DNA barcoding upon some of the measures of taxonomic capacity in Canada described above is not possible. Comparative analyses of taxonomic research productivity between earlier years and the past few are made much more difficult by the diversification of journals that publish results of such studies and the delay between species discovery and publication. Instead, we followed a more direct approach and contacted researchers receiving funding through the large NSERC network and Genome Canada grants for barcoding. We assessed the impact of DNA barcoding upon taxonomic research capacity by asking recipients of DNA barcoding funds a series of questions relating to funding, personnel, and taxonomic productivity resulting from barcoding funds and other sources of research support.

Results

Patterns in taxonomic research

Publication data

Our data include the description of 1021 new species and 132 new genera (Table 1) plus four new families and 1 new order. These were distributed among 732 papers assessed as being taxonomic in nature out of the total of 6739 research articles published on any topic by the three target journals over the total 9 years surveyed.

The number of new genera described falls off dramatically over time (by over 72%), decreasing from a total of 61 in the 1980 time period for all three journals combined to only 17 in 2000 (χ^2 = 15.7, p < 0.005; Table 1). The number of new families described is too small for statistical analysis (one new family in CJZ in each of 1980 and 1990 time periods and two new families in CJB in 1990).

The number of taxonomy papers published decreased from 307 to 103, a decline of 66%. As a proportion of all papers published, this represents almost a halving, from 12.5% to 6.5% of the total (a decrease of 47.8%). The number of papers that described new species also decreased substantially, by 62%, from 194 to 74 (Table 1). As a proportion of all papers published, those that included new species descriptions fell by 41%, from 7.9% of the total to 4.7%. The total number of species described fell by 60%, from 412 in the 1980 period to only 167 in 2000, although there was a slight increase in the total number of species described in 1990 (to 442).

These totals obscure some important patterns (Fig. 1). Both CJZ and CJB had increases in species descriptions between 1980 and 1990 (from 85 to 166 and from 92 to 144, respectively) so that the similarity in totals when summed for all three journals between the first two time periods resulted from a marked decline in species descriptions in TCE (from 235 to 135). Furthermore, between 1990 and 2000 the number of new species described in CJZ dropped by more than an order of magnitude. Thus, all three journals showed a marked decrease in the number of new species descriptions in 2000, but the decline occurred earlier in TCE than for either of the other two journals. Unsurprisingly, analysis of variance shows that there is significant variation in number of new species descriptions over the three time periods (F = 9.64, p > 0.001), significant variation in this pattern among journals (F = 5.49, p < 0.02) and a significant interaction between the two variables (F = 3.2, p < 0.04).

The decrease in number of species described is entirely a result of a decline in output by CbR, as the number of species described by nCbR was higher in 2000 (74) than in 1980 (58) (Fig. 2). This is in stark contrast to the decline from 354 to 313 and then 93 published by CbR over the three time periods (a decline of 74%). The decline in CbR contribution to species descriptions is highly significant for each journal (CJZ: χ^2 = 13.2, p < 0.005; CJB: χ^2 = 35.7, p << 0.001; TCE: χ^2 = 30.5, p << 0.001; raw data in Table 2). This represents a substantial reduction in the proportion of all new species descriptions published in Canadian journals that were authored by CbR (from 86% of the total to 56%). The decline in publication of new species descriptions in Canadian journals is therefore caused entirely by a drop in contributions by CbR.

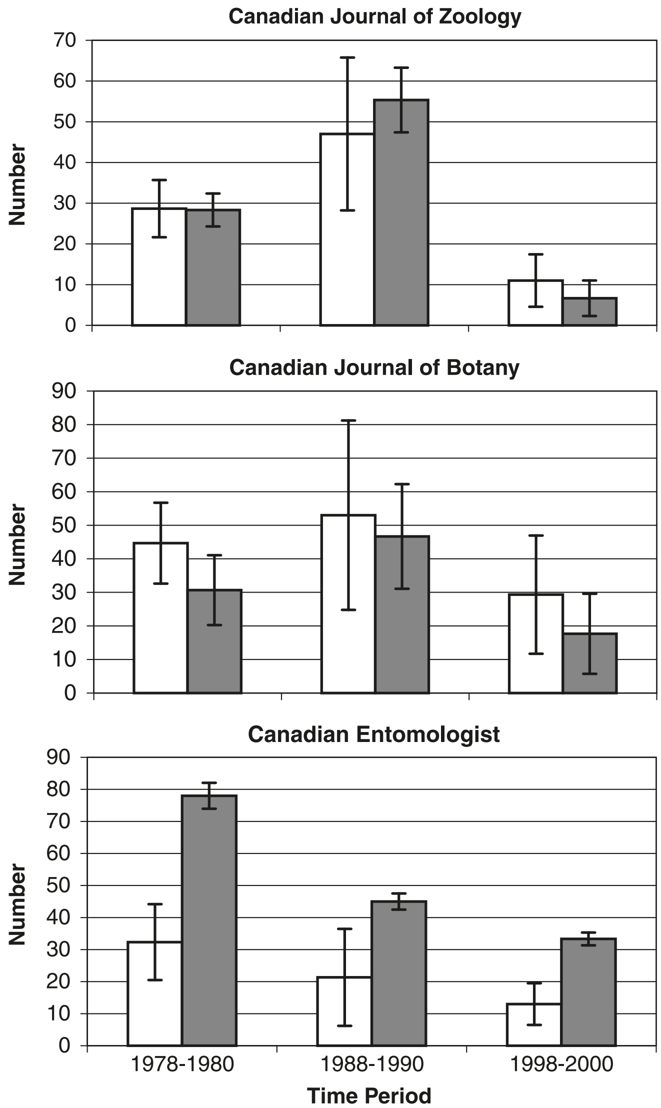
Table 2 also shows the relative contribution of university and non-university Canadian researchers towards the description of new species over time and across journals. There is an increase in the proportion of all species described by CbR that were authored by university researchers, from 23% to 37%. There is substantial and complex variation among journals over time in this variable. CJZ and CJB show an increase in the proportion of descriptions from university-based Canadian researchers between 1980 and 1990, but the numbers for 2000 are rather low for meaningful analysis (with a total of six and nine species described by CbR in CJZ and CJB, respectively). TCE shows more than a tripling (from 10.5% to 32.8%) in the proportion of species described by university-based CbR compared

Table 1. Summary statistics for systematic and taxonomic papers published in the *Canadian Journal of Zoology* (CJZ), *Canadian Journal of Botany* (CJB), and *The Canadian Entomologist* (TCE) for three time periods.

		Number of paper types							
Journal and time period	Total no. of papers	Systematics	Taxonomic	With species descriptions	With new species described	With species CbR described	With key	With phylogeny	With new genera
CJZ									
1980	930	86	86	51	85	70	13	0	7
1990	1217	141	131	93	166	97	15	12	17
2000	770	33	14	10	14	6	1	16	3
CJZ									
1980	989	134	125	70	92	56	23	6	24
1990	1154	159	128	61	141	89	29	9	27
2000	569	85	53	33	53	9	41	24	10
TCE									
1980	539	97	96	73	235	228	42	3	30
1990	330	65	63	50	135	117	34	4	10
2000	241	39	36	31	100	78	30	1	4
Total									
1980	2458	317	307	194	412	354	78	9	61
1990	2701	365	322	204	442	303	78	25	54
2000	1580	157	103	74	167	93	72	41	17

Note: CbR, Canadian-based researcher.

Fig. 1. Change in mean (±SD) number of taxonomic research articles (open bars) and mean (±SD) number of new species described (shaded bars) for each 3-year period in the *Canadian Journal of Zoology*, *Canadian Journal of Botany*, and *The Canadian Entomologist*.

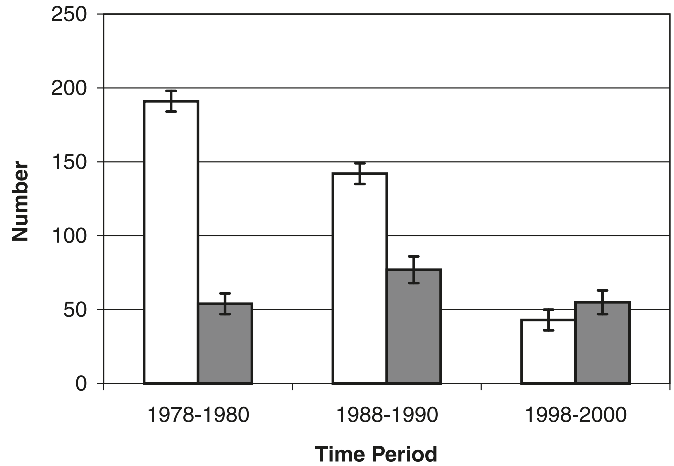


with their governmental counterparts between 1980 and 2000 time periods (χ^2 = 17.7, p << 0.001). The overall pattern is a significant increase in the proportion of all species described by university researchers over that by governmental CbR (χ^2 = 20.9, p << 0.001). Nonetheless, the number of new species described by university-based CbR still decreased substantially (from 97 to 27 for 1980 and 2000 time periods, respectively, summed across journals).

We have shown a significant reduction in the quantity of taxonomic work published by Canadians and (or) published in Canadian journals, but what of the quality of such work?

As taxonomic revisions are by far the most useful results of taxonomic research, we believe change in their frequency to be a particularly cogent indicator of the state of the subject and summary data for them are given in Table 3. The total number of revisions published in the three target journals rose from 32 to 38 between 1980 and 1990 time periods

Fig. 2. Variation in the mean (±SD) number of new species descriptions over time by researchers based in Canada (open bars) versus those living elsewhere (shaded bars) published in the *Canadian Journal of Zoology*, *Canadian Journal of Botany*, and *The Canadian Entomologist*.



but fell to 15 in 2000, a decrease (from 1980) of over 53%. For revisions performed by CbR, the equivalent numbers are 27 (1980), 30 (1990), and 8 (2000); a decline of 70%.

The proportion of taxonomic papers that included an identification key shows a significant increase over time when summed across journals (χ^2 = 14.3, p < 0.001; Table 1). This is a recent increase, as ~25% of taxonomic papers included a key in both 1980 and 1990 time periods, but in 2000 this proportion had almost trebled to 70%. However, there is substantial variation among journals in this variable. Both CJB and TCE show a marked increase in the proportion of taxonomic papers that include a key (especially between 1990 and 2000 time periods), while there is a halving in this variable in CJZ over the same time period.

Personnel

The number of taxonomists employed in insect and arachnid taxonomic research at Agriculture Canada's K.W. Neatby building declined from 31 in 1980 to 25 in 1990, and then to 17 in 2000 (Fig. 3) (Dang 1992; Huber and Cumming 1999; J.M. Cumming, personal communication). Indeed, staffing levels in 2000 were exactly the same as they were in 1950! Since 2000 there has been somewhat of a turnaround, with an additional 5 research scientists being employed and only 2 retiring, so that there is now a total of 20 (J.M. Cumming, personal communication).

Table 4 shows data from the lists compiled by Danks and Ridewood (1989) and Danks and Goods (1997). The number of people that listed taxonomy as a major interest was very similar across the two surveys (136 and 133, respectively). Although the number of university professors declined by 16%, graduate students by 33%, and workers at CNC by 32%, these were offset by increases in the number of amateurs and retirees, which both doubled. The number of research assistants remained constant. If (and this may be "a large if") it is predominantly the graduate students, university professors, and staff at the national collection who are most likely to produce original taxonomic research, the

Table 2. Species descriptions published in the *Canadian Journal of Zoology* (CJZ), *Canadian Journal of Botany* (CJB), and *The Canadian Entomologist* (TCE) by Canadian-based researchers (CbR) located in universities, government institutions, or non-affiliated personnel versus non-Canadian-based researchers (nCbR).

	CbR			
Journal and time period	University	Government	Other	nCbR (total)
CJZ				
1980	36	34	0	15
1990	70	24	3	69
2000	1	5	0	8
CJB				
1980	28	27	1	36
1990	31	57	1	52
2000	7	2	0	44
TCE				
1980	33	195	0	7
1990	17	99	1	18
2000	19	39	20	22

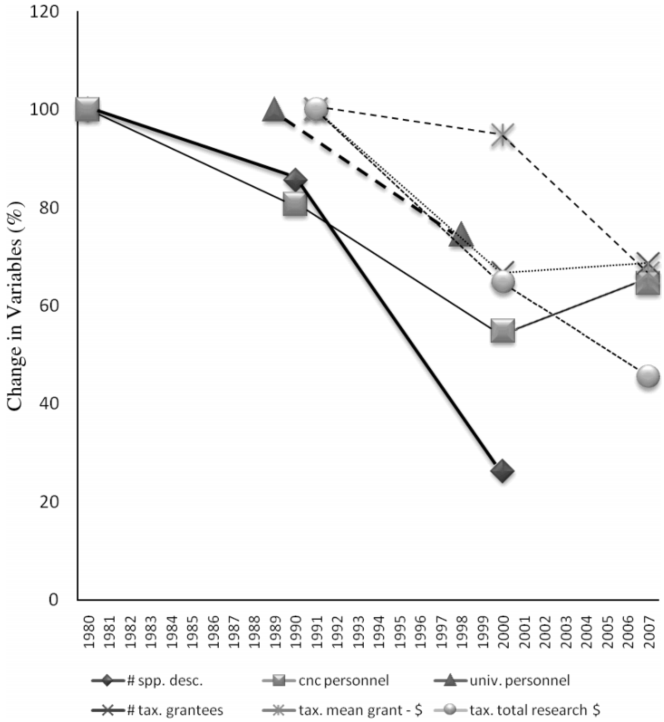
Table 3. Data on number of revisionary studies and number of new species described in revisionary studies published in Canadian publications by Canadian-based researchers (CbR) and non-Canadian-based researchers (nCbR).

	CbR									
	University		Government		Total		nCbR (total)		Grand total	
Publication and time period	No. of papers	No. of species	No. of papers	No. of species	No. of papers	No. of species	No. of papers	No. of species	No. of papers	No. of species
CJZ										
1980	2	2	0	0	2	2	1	2	3	4
1990	5	7	2	15	7	22	3	4	10	26
2000	0	0	0	0	0	0	2	3	2	3
CJB										
1980	3	1	6	4	9	5	4	3	13	8
1990	4	2	7	37	11	39	5	9	16	48
2000	0	0	1	0	1	0	3	1	4	1
TCE										
1980	1	1	15	85	16	86	0	0	16	86
1990	1	1	10	58	12*	60*	0	0	12	60
2000	3	7	3	18	7*	45	2	6	9	51
Total										
1980	6	4	21	89	27	93	5	5	32	98
1990	10	10	19	110	30*	121*	8	13	38	134
2000	3	7	4	18	8	45	7	10	15	55
QE										
1980	2	2	0	0	2	2	4	176	6	178
1990	2	5	1	41	3	46	6	29	9	75
M										
1980	0	0	6	70	6	60	1	5	7	65
1990	0	0	5	15	6*	23*	0	0	6	23
NRC										
2000	2	18	0	0	2	18	0	0	2	18
Grand total										
1980	8	6	27	169	35	155	10	186	45	341
1990	12	15	25	166	39*	192*	13	39	31	217
2000	5	25	4	36	10*	63	7	10	17	7

Note: CJZ, *Canadian Journal of Zoology*; CJB, *Canadian Journal of Botany*; TCE, *The Canadian Entomologist*; QE, *Quaestiones Entomologicae*; M, *Memoirs of the Canadian Entomological Society*; NRC, National Research Council Monograph Series.

*Totals differ from the sum of university and government CbR as a result of work by "independent" researchers.

Fig. 3. Change in variables related to taxonomic productivity in Canada over the periods 1978–2000. Data for the earliest time period available are set at 100%.



number of personnel over the 8 years between surveys declined by 28%, from 83 to 60 (χ^2 = 6.84, p < 0.01; Fig. 3).

Funding

The number of grantees performing traditional taxonomic research funded by GSC18 declined by 23%, from 48 to 37, between 1991 and 2007 (Table 5). This is a significant decrease compared with the number of grantees in all other areas of research funded by GSC18, which increased substantially over the same time period (χ^2 = 10.26, p < 0.005). As six grantees received funds for taxonomy from GSCs other than GSC18 in 1991 and none did so in 2007, the total number of taxonomists funded by NSERC over this period fell by 31.5%.

In 1991, the mean grant in taxonomy was $23 720 (SD = $14 567, n = 48), increasing to $27 324 (SD = $17 022, n = 36) in 2000 but decreasing in 2007 to $22 837 (SD = $13 202, n = 37), almost $1 000 below 1991 levels (Table 5). Between 1991 and 2000, this corresponds to a mean grant increase of 15%, which was above the mean increase (~6%) for all areas funded by GSC18. But in comparing 2007 and 1999, the data indicate a decrease of 4% in mean grant size in taxonomy compared with an overall increase of 0.7% for other areas funded by GSC18.

Analysis of variance demonstrates that grant sizes for taxonomy have averaged significantly less than those for other areas of research funded by GSC18 (F = 11.28, p = 0.0008). Tukey's HSD test indicates that the difference was significant in 1991 and 2007 (for both years, p < 0.01), but not in 2000.

Total expenditure on taxonomic research by GSC18 fell by 13% between 1991 and 2000 and by 26% between 1991 and 2007. This is compared with an overall 37% and 64% increase in total funds available to non-taxonomic research funded by GSC18 in 2000 and 2007, respectively. Total NSERC expenditure on taxonomy through discovery grants (i.e., including GSCs other than 18) fell by 24.5% (~$336 000) between 1991 and 2000 and by 38.5% (~$530 000) between 1991 and 2007.

Table 4. Number of taxonomists working on insects and related taxa (data compiled from Danks and Ridewood (1989) and Danks and Goods (1997).

	1989	1996
Professors	25	21
Graduate students	30	20
Research assistants	10	10
Canadian National Collection (CNC)	28	19
Other governmental	26	29
Consultants	3	4
Retired	7	16
Amateurs	7	14
Totals	136	133

Inflation has resulted in the Canadian dollar being worth 35.1% less in 2007 than in 1991. Thus, mean grant size in taxonomy to applicants to GSC18 decreased by 40% between 1991 and 2007 when measured in 2007 dollars. Similarly, by 2007, the amount of money being spent on taxonomic research by NSERC had fallen by more than half compared with 1991 levels (Table 5). This contrasts with an overall increase of 21% over inflation in funding to all other areas of research funded by GSC18 combined. As the mean grant size has not increased, this overall increase in expenditure to all grantees is caused by an increase in the number of researchers receiving funds.

The impact of DNA barcoding

Fifteen of the 24 researchers responded to our survey questionnaire. In total, they indicate that almost three million dollars was being spent on taxonomic research in their laboratory as a result of funds from barcoding grants, this was over 4 times the total available to the same researchers from other funds (Table 6).

The number of new species being discovered in these laboratories resulting from barcoding funds was increased over that occurring from other research grants by a factor of more than 5, although the total number of species expected to be described by the time currently available funds are expended only doubled. This indicates that there will be a taxonomic legacy of increased species descriptions that will last well beyond the duration of current funding from barcode-related grants.

Variance in species description rates among individual respondents was high. This is due, in part, to the great diversity in research cultures of the participants: new species discoveries in birds being much rarer than in insects or fungi, for example. Nonetheless, the overall pattern is clear: funds available for DNA barcoding have sped up the rate of discovery of new species substantially.

More personnel are being trained in taxonomy as a result of DNA barcoding funds. Respondents report that a total of 47 HQP are being trained from this funding source, more

Table 5. Annual Natural Sciences and Engineering Research Council of Canada (NSERC) expenditures on taxonomy through discovery grants in 1991, 2000, and 2007 compared with other expenditures through the Grant Selection Committee 18 (GSC18).

	1991		2000		2007	
	Taxonomy	Other	Taxonomy	Other	Taxonomy	Other
Number of grantees	48 (54)	367	36 (37)	468	37 (37)	599
Mean grant size ($)	23.720 (25.547)	29.300	27.324 (28.065)	31.015	22.837 (22.837)	29.505
Mean grant size corrected to 2007 dollars	32.045 (34.292)	39.584	31.64 (32.505)7	32.505	22.837 (22.837)	29.505
SD grant size ($)	14.567 (16.514)	17.279	17.022 (17.379)	18.362	13.202 (13.202)	16.413
Total spent ($1000s)	1138.550 (1374.667)	10752.990	983.667 (1038.413)	14514.870	844.980 (844.980)	17673.360
Total spent corrected to 2007 dollars ($1000s)	1538.181 (1857.175)	14527.276	1139.282 (1202.690)	16811.120	844.980 (844.980)	17673.360

Note: Values in parentheses include taxonomic expenditures from GSC18 and other GSCs.

Table 6. The impact of DNA barcoding upon funds available, species discovery, and training in the laboratories of 15 researchers.

	Researcher															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Barcode funds ($1000s)	75	315	200	500	25	75	130	200	25	62.5	170	270	230	425	275	2977.5
No. of M.Sc. students		1		2	1		2	1	1			1		1		10
No. of Ph.D. students	1	1	2	1		1				1	1			1	2	11
No. of postdoctoral fellows		1	2	3			1	1			1	1	2	2	1	15
No. of honours students		3						2						2		7
No. of assistants													2		2	4
Total highly qualified personnel (HQP)	1	6	4	6	1	1	3	4	1	1	2	2	4	6	5	47
No. of new species described	3	5	5			5		5				1		6	4	34
Total new species	213	29	27	10		20	22	55	10	11		21	20	48	48	534
No. of new synonymies	10	10	6	5		5	6		2	3		20		39	2	108
Other funds ($1000s)*	18	130	125	100			30		100		75		25	29	50	682
No. of M.Sc. students *				5					2			1	1	1		10
No. of Ph.D. students*				5								2			4	11
No. of postdoctoral fellows*		1		10			1	1							2	15
Total HQP*		1		20			1	1	2			3	1	1	6	36
No. of new species*	1			5				25							1	32
Total of new species*	61			15					10				3		4	93
No. of new synonymies*	1			10					5							16

*Without DNA funds.

than the total number of taxonomists the same researchers would have trained otherwise (36). Thus, DNA barcoding is permitting a 133% increase in the number of taxonomists being trained in Canada.

We can use research in the senior author's laboratory as a detailed example. Funds available through the NSERC barcoding network grant have permitted the training of one postdoctoral fellow and one Ph.D. student and have funded research costs for two undergraduate honours theses. By the time these funds are expended in late 2010, the postdoctoral fellow will likely have been replaced by a second; an additional M.Sc. will have almost been completed, as well as at least one additional undergraduate honours thesis. Only the honours thesis students would likely have been trained in taxonomy in the absence of these funds, but they would have used traditional approaches only. The postdoctoral fellow has completed a revision of the Canadian species of one of the most economically important genera of bees — *Megachile* Latreille, 1802 (a revision of over 200 manuscript pages in length, not including over 200 illustrations (Sheffield et al. 2010). The Ph.D. student has published or submitted several portions of what will soon be a complete revision of Canadian species in one of the most difficult to identify, yet most commonly collected, groups of bees in North America, the subgenus *Dialictus* of the genus *Lasioglossum* Curtis, 1833 (Gibbs 2009*a*, 2009*b*). There were 288 valid names in this group before this work started. Similar to the situation with *Megachile*, copiously illustrated keys will be written for the Canadian *Dialictus* fauna. Several smaller taxonomic studies dealing with different components of the world's *Dialictus* have also been completed (Gibbs 2009*c*, 2010). The net result is that DNA barcoding has already permitted four small-scale and two complete large-scale taxonomic revisions to be completed in the senior author's laboratory (Sheffield et al. 2010; J. Gibbs, submitted[5]). None of these would have been completed in the absence of barcoding funds. In contrast, over the same period, only one M.Sc. student would have been trained in taxonomy in the same laboratory.

The increased taxonomic capacity that these funds have allowed is far more extensive than the aforementioned account suggests. This is simply because of the additional synergism resulting from a critical mass of personnel studying bee taxonomy. Some of this synergy has involved "identification services" for biodiversity surveys. These have resulted in far more accurate identifications than would have been possible otherwise (H.T. Ngo, J. Gibbs, T.L. Griswold, and L. Packer, unpublished data; A. Taylor and L. Packer, unpublished data). Without this assistance, errors owing to incompletely or inaccurately known taxa would have crept into the literature on these groups as has happened in the past (e.g., Giles and Ascher 2006; Grixti and Packer 2006). Comparison of the taxonomic decisions in these papers with what we now know based upon DNA-barcoding-based studies of the bee fauna suggests that at least 23% of the individual specimens in these papers may have been misidentified.

This critical mass of personnel has also facilitated extra taxonomic research publications, even though DNA barcoding was not a method used in the research. These include traditional, morphology-based, identification keys to the genera of bees of Eastern Canada (Packer et al. 2007).

Discussion

The data presented above permit a detailed assessment to be made on the status of taxonomic research in Canada. Some of our information goes back 30 years (publication data for example), whereas other variables could only be assessed for more recent time periods (such as sizes of research grants). Nonetheless, from these disparate pieces of information, we can gauge the recent trend in taxonomy in Canada and to evaluate the impact of DNA barcoding upon the field. We first address some of the variation in taxonomic capacity and explore some possible explanations for the patterns that we have observed. Then we assess the impact of DNA barcoding upon taxonomic capacity, and finally, we present some recommendations aimed at ensuring the further revitalization of this essential area of research.

Between 1980 and 2000 there was a marked decline in the amount of basic taxonomic research being carried out in Canada in terms of the number of papers published, species and genera described, total amount of funds provided to university-based researchers from NSERC, and the number of personnel performing taxonomic work at universities, Agriculture Canada's National Collection of Insects and Arachnids, and elsewhere (Fig. 3).

There are many possible reasons for the observed decrease in taxonomic productivity. We highlight four: (1) editorial policy within journals, (2) changes in the number of personnel conducting taxonomic research, (3) reduced funding, and (4) the changing work environment experienced by taxonomists.

(1) Editorial policy within journals. The first possibility can be readily dismissed. The decline in published taxonomic research in Canadian journals between 1980 and 2000 is purely a result of reduced activity by Canadian researchers, as publication rates for non-Canadians in the three journals actually increased. This suggests that the decline in the taxonomic output of CbR in our three target journals could not have been caused by changes in editorial treatment of submitted papers in taxonomy. This is all the more surprising when the loss of several important alternative venues for taxonomic research in Canada in the 1990s is taken into consideration. *Quaestiones Entomologicae* and *Memoirs of the Canadian Entomological Society* ceased publishing in 1990 and 1997, respectively. Sixty-two new species were described by CbR in these two journals in the 1980 time period and 71 in the 1990 time period. The National Research Council Monographs series might be considered an alternative source for works that might have appeared in these two journals. In the 2000 time period, 18 new species descriptions were published in this venue. These alternative publication sources thus show a 71% decline in new species descriptions, very similar to that found for the other journals (74%). One might have expected to see an increase in taxonomic research in TCE or CJZ when *Quaestiones Entomologicae* and *Memoirs of the Canadian*

[5] J. Gibbs. Revision of the metallic *Dialictus* of Canada (Hymenoptera: Halictidae: *Lasioglossum*). Submitted for publication.

Entomological Society ceased publishing, but the overall decline continued and was not compensated for by species descriptions in the NRC Monograph series.

The remaining three possible explanations require more detailed consideration.

(2) Personnel. Certainly the decrease in number of personnel performing taxonomic research, both in universities and in governmental organizations, will have contributed to the results for overall publication rate decline. It is not possible to make a firm connection between these two variables for a variety of reasons, one of which being that we do not have the required biographical information for taxonomists and their publications going back to the late 1970s. Nonetheless, it would be impossible for the taxonomists in the largest assemblage of such professionals in Canada to maintain 1980 levels of productivity in the 2000 time period when their numbers had decreased by almost 50%! The reduction in staffing levels at the CNC is the most probable explanation for the decrease in proportion of new species descriptions performed by government-based scientists over time, although the reduction in description rates is substantially less than that in personnel, suggesting that those remaining were working harder. This could have been assisted by the fact that the reduction in number of technical assistants at the CNC did not decrease as dramatically as the number of scientists (J.M. Cumming, personal communication). The increased per-capita productivity among CNC personnel also suggests that their revisionary work was not overly hampered by exhortations to produce more narrowly focused, problem-solving publications dealing with small, directly applied topics.

The comparatively small reduction in number of university-based taxonomists was accompanied by a somewhat larger decrease in the number of graduate students doing taxonomy research. Yet it is not our impression that the numbers of students interested in doing research in taxonomy has declined, rather our impression is in direct opposition to this, although we have no hard data on this topic. However, the opportunities for such students, in terms of total funding available to potential supervisors, has not kept pace with the costs of doing the work. Of particular importance here are the expenses associated with travel — an essential activity in taxonomic work both in terms of visits to museums housing type and other material and in obtaining additional specimens through fieldwork. The travel cost of living has increased at a faster rate than inflation.

(3) Funding. The total amount of money available for taxonomic research from NSERC's GSC18 declined between 1991 and 2000 granting periods largely because the number of people receiving such moneys fell. It fell further between 2000 and 2007 solely as a result in reduced funds per researcher. The net result is that the mean grant to a taxonomist in 2007 was worth almost 40% less than the mean grant in 1990.

Mean amounts of funding per successful applicant in taxonomy actually increased above background levels for other areas funded by GSC18 between 1991 and 2000, but this was likely due to one-time-only top-ups for systematic research that resulted from the implementation of NSERC's reallocation process. Furthermore, when averaged across all taxonomists, even these increases did not quite keep up with inflation. These disbursements were in maximum amounts of $16 500 for each researcher, this being considered sufficient for the professors to hire one additional graduate student. These moneys were meant to have been reallocated to taxonomists performing research of relevance to Canadian agricultural and forestry concerns. In practice, they were disbursed to systematists irrespective of area of research activity: not necessarily to those doing taxonomic studies of the Canadian biota, or even doing taxonomy at all. The dramatic decline in mean grant size for taxonomists between 2000 and 2007 is partly a result of the loss of these funds. But the point remains that taxonomists are now at a distinct disadvantage compared with other researchers funded by GSC18. Given the recent changes in grant awarding procedures implemented by NSERC, it will be very important to assess how taxonomists fare compared with other researchers in evolution and ecology over the next few years.

Decreases in research funding have a double impact upon taxonomic research capacity: less publications and reduced opportunity to train the next generation of taxonomists with resultant reduced competitiveness in the job market (see below).

(4) Changing expectations. Non-traditional aspects of taxonomic work have certainly increased in recent decades. The production of Web-based interactive keys (Walter and Winterton 2007), Internet-based museum and biodiversity survey-related databases (for example see University of Alberta 2009), contributions of data to the Global Biodiversity Inventory Fund (GBIF), and contributions to All Taxon Biodiversity Inventories (ATBIs) are all things that simply could not have happened in 1980, yet they are all important and extremely time-consuming activities that take away from the task of actually describing taxa. The current technological quantum leap forward that is occurring in the laboratories of taxonomists with the implementation of Web-based tools (Bisby 2000; Anonymous 2002; Bisby et al. 2002; Godfray 2002) should eventually speed up the process of species descriptions (Gewin 2002), although the time required to set up such efforts is enormous and must, at least temporarily, detract from descriptive work. Furthermore, the quality of some of this information is sometimes sufficiently poor for it to be a disservice to taxonomy (Q.D. Wheeler 2004; T.A. Wheeler 2004), with the result that considerable amounts of time are required of taxonomists in correcting the errors. Again, the policing that is required for such venues can only be provided by skilled, funded researchers whose work environment permits them the time to ensure high quality of Internet-published taxonomic research. This is yet another drain on the taxonomist's time.

In summary, decreased taxonomic productivity in Canada between 1980 and 2000 was likely the result of decreases in the number of taxonomists and decreases in the real value of funds for each taxonomist's research. The more recent proliferation of demands upon taxonomists' time and further reduction in mean research grant size would also have substantially reduced the resources available for species descriptions up to the present day.

Taken overall, our historical data suggest that taxonomy in Canada might have become extinct sometime in the next decade. Extrapolating from our (admittedly limited) data, the number of species described, the number of professors performing taxonomic research, and the total amount of GSC18 funds spent on taxonomy (corrected for inflation) would all likely have decreased to zero by 2020.

The impact of DNA barcoding

Results from our survey of personnel being trained and taxonomic research productivity arising from DNA barcoding research grants are summarized in Table 6. As can be seen, there has been a tremendous increase in all areas of training and productivity as a result of funds for DNA barcoding. When research funds to eligible NSERC grantees alone are considered, a mean of over $330 000 in taxonomic funding has been made available per annum during the lifetime of the network. If this amount is added to the totals in Table 5, we find that research funds currently available for taxonomy have increased above those available in 1991. Even when the increased value of earlier grant awards owing to subsequent inflation are included, the amount of funds made available through GSC18 and DNA barcoding are now similar to those that were available at some point between 1991 and 2000. Considering that there are more taxonomists in receipt of funds from the barcoding network grant than included in the above calculations (through lack of response to the questionnaire), DNA barcoding funds have made up for more than the other losses in funding to university-based researchers over the past 20 years. Although continued funding appeared likely given how well received the international barcoding initiative was by Genome Canada, the cutting of all new funds for this agency in the 2009 federal budget has been a severe blow to Canada's re-emerging taxonomic capacity.

Future prognoses and some recommendations

Our data suggest that rather than taking funds away from traditional taxonomy, the advent of DNA barcoding is permitting a renaissance of this crucial area of research in Canada. It is certainly true that not all funds for barcoding are being used for combined morphological and molecular taxonomy (some are required for technological advances, computational work, etc.). Nonetheless, the proportion of these funds used for integrative approaches has resulted in a substantial overall increase in the resources available for taxonomic research at Canadian universities and has substantially increased species discovery and description rates.

But there is a potential downside to the impact of DNA barcoding upon taxonomy in Canada (and elsewhere). This is the sheer number of species that are new to science that DNA barcoding is uncovering: in some instances over an order of magnitude more than previously thought to occur (Hebert et al. 2004; Smith et al. 2008). The process of formally describing this additional diversity suggests that estimates of the size of Wilson's army (the term used to describe the number of new taxonomists required to complete the task of inventorying the world's biota; Wilson 2000) needs to be increased substantially.

We believe that developments in two areas are required for Canada to capitalize fully on the internationally reknowned breakthroughs that DNA barcoding provides: an increase in the number of faculty and government positions for taxonomists and specific research funds dedicated to the descriptive work that barcoding has shown is even more necessary than previously thought.

Additional positions for taxonomists at Canadian universities are not going to arise through decision making by individual university departments or faculties. Indeed, the data we have collated suggests that trained taxonomists would find it increasingly difficult to obtain employment at universities. In practice, taxonomists are most likely to be contenders for university positions advertised in areas of evolutionary biology and ecology. Those that include phylogenetic approaches could focus job applications in the former category; those involved in biodiversity survey research might be suitable for positions in the latter area. However, such people will have been trained in research laboratories that have usually been significantly underfunded compared with other areas of ecology and evolution. Given the "back-end-loaded" nature of serious revisionary study, taxonomists would face a competitive disadvantage compared with ecologists and evolutionary biologists applying for the same university positions through having reduced research productivity. Taxonomists are also disadvantaged by the ever increasingly popular bean-counting approach to assessment of the relative worth of different academics through citations and other "impact" ratings; it being well known that taxonomic work is substantially undercited (being used for identifications without reference) while having a value that can extend for over a century, when high impact more "topical" research products are long forgotten (Krell 2000, 2002; Packer et al. 2009). These disadvantages become a vicious circle from which HQP may be hard pressed to escape.

Centralised funding for university-based positions in taxonomy, along the lines of the University Research Fellowship and Women's Faculty Award programs since the 1980s or the more recent Canadian Research Chair program, is required. It is possible that only 10–20 of these positions could return us to 1980 personnel and productivity levels. However, given the increasing complexity of taxonomic research as noted above, the critical need to have more people capable of identifying invasive species and other economically important organisms and Canada's obligations in the realm of taxonomy under various national (e.g., the Species At Risk Act) and international initiatives (e.g., the Rio Convention on Biodiversity), even returning to 1980 levels of productivity will not be enough. Given the time-consuming nature of maintaining research collections and completing state-of-the-art identification-related research output, each position should come with sufficient funding for hiring at least one full-time technician for the duration of the faculty members' grant worthiness. This requires a greater commitment of funds than accrues with standard university positions, but no more than is the case with the Canadian Research Chair program. With central (NSERC) funding, the possibility of hiring well-funded taxonomists would encourage university administrators to actively consider hiring such people through narrowing the funding gap between taxonomists and medical researchers (for example).

It is also clear that different assessments of taxonomic funding applications are required. Given the unusual nature of taxonomic research career development (slow accumulation of knowledge), impact (resulting in fewer larger scale publications later in life, e.g., Larson et al. 2000), and recognition by the wider community (even revisionary studies that are commonly used are rarely cited), these funds should be dispensed by a committee made up mostly of practicing taxonomists. Such funding should be primarily for larger scale revisionary works. The committee should consider Web-based identification keys, GBIF-style databasing, and biodiversity inventorying as serious research output and recognize the massive amount of work required to prepare a single taxonomic monograph with concomitantly low overall productivity of such items.

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