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A quantitative analysis of the state of knowledge of turtles of the United States and Canada

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Abstract. The "information age" ushered in an explosion of knowledge and access to knowledge that continues to revolutionize society. Knowledge about turtles, as measured by number of published papers, has been growing at an exponential rate since the early 1970s, a phenomenon mirrored in all scientific disciplines. Although knowledge about turtles, as measured by number of citations for papers in scientific journals, has been growing rapidly, this taxonomic group remains highly imperiled suggesting that knowledge is not always successfully translated into effective conservation of turtles. We reviewed the body of literature on turtles of the United States and Canada and found that: 1) the number of citations is biased toward large-bodied species, 2) the number of citations is biased toward wide-ranging species, and 3) conservation status has little effect on the accumulation of knowledge for a species, especially after removing the effects of body size or range size. The dispersion of knowledge, measured by Shannon Weiner diversity and evenness indices across species, was identical from 1994 to 2009 suggesting that poorly studied species remained poorly-studied species while well-studied species remained well studied. Several species listed as threatened or endangered under the U.S. Endangered Species Act (e.g., *Pseudemys alabamensis*, *Sternotherus depressus*, and *Graptemys oculifera*) remain poorly studied with the estimated number of citations for each ranging from only 13-24. The low number of citations for these species could best be explained by their restricted distribution and/or their smaller size. Despite the exponential increase in knowledge of turtles in the United States and Canada, no species of turtle listed under the Endangered Species Act has ever been delisted for reason of recovery. Therefore, increased knowledge does not necessarily contribute appreciably to recovery of threatened turtles.

Keywords: Canada, conservation, Endangered Species Act, knowledge, literature, turtles, United States.

Introduction

Every publishing scientist is aware of the challenge of keeping abreast of the inexorably increasing volume of newly published literature in the "information age". This explosion of information (Adair and Vohra, 2003) is true across all science disciplines, including herpetology (Wake, 2008). An illustration of the rapid rate of increase is provided by Kaser (1995) for the National Federation of Abstracting and Information Services, an organization that tracked the growth of information services (also called secondary information services) for more than thirty-five years. These services acquire, index and host literature for later location and retrieval, often via subscription. According to Kaser (1995), the number of abstracts published by twelve leading information services in 1957 was about 555 000. In 1977 the number was 2.24 million and by 1997 is rose to about 3.7 million. Even as early as 1990, Thorngate (1990) estimated that psychologists collectively publish 100 articles per day or about one every 15 minutes!

Turtles have not escaped the information explosion with recent large increases in knowledge driven, in part, by the increasingly imperiled status of this taxonomic group (Gibbons et al., 2000; Klemens, 2000). The United States and Canada are now home to 58 native turtle species (Ernst and Lovich, 2009; Ennen et al., 2010; Murphy et al., 2011), or almost 20% of the world's total. Of these, at least 22 ($\sim$41%) require attention conservation action as vulnerable, threatened or endangered species under the UN Convention on International Trade in Endangered Species (CITES), the International Union for the Conservation of Nature and Nat-

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ural Resources (IUCN) Red List, or the Endangered Species Act (ESA). This includes 14 species (25%) that are protected under the ESA, one of the strongest environmental laws in the world (Ernst and Lovich, 2009). However, the status of knowledge for turtles, including those of conservation concern in the United States and Canada, has never been quantified despite recent syntheses of the biology and conservation of turtles of the United States and Canada (Ernst et al., 1994; Ernst and Lovich, 2009).

The purpose of this paper is to provide a quantitative assessment of knowledge indices for turtle species in North America north of Mexico. Measuring knowledge is controversial due both to the difficulty of defining knowledge and the complexity of creating metrics for its meaningful quantification (Carter, 1998; Alavi and Leidner, 2001; Housel and Bell, 2001). Despite the disagreements for defining and measuring knowledge we outline a series of knowledge indices for our analysis of the state of knowledge of turtles in the United States and Canada. We asked two basic questions: 1) how fast is information on turtles accumulating, and 2) is it accumulating evenly, or are their biases related to taxonomic status (genus or species), body size, conservation status, and range-wide distribution? We characterize recent knowledge accumulation patterns in the region of interest by comparing Ernst et al. (1994) and Ernst and Lovich (2009).

Materials and methods

For the purposes of this analysis we measured knowledge for turtles as numbers of publications or amount of written text on turtle genera and species for specific time periods. Thus, the focus is on tangible metrics. Intangibles like the impact or scope of publications or the journals they appear in are not considered because different valuations and relative usefulness do not constrain definitions of knowledge (Housel and Bell, 2001). As such, each turtle publication counted or measured in our analyses is treated as if its knowledge content was the same as all others, an assumption that is obviously not always met since some definitions of knowledge include deep vs. superficial forms (Thorngate, 1990; de Jong and Ferguson-Hessler, 1996). For details on epistemology beyond the scope of this paper the reader should consult other sources such as de Jong and Ferguson-Hessler (1996) and Alavi and Leidner (2001).

Syntheses of knowledge of turtles in the United States and Canada have a long and distinguished modern history. The lineage starts with Clifford Pope's (1939) "*Turtles of the United States and Canada*". His book was followed by the great scientist-story teller Archie Carr's (1952), "*Handbook of Turtles: the turtles of the United States, Canada, and Baja California*", in 1952. Those two works stood as early monuments to efforts to catalog knowledge of turtles until the publication of Ernst and Barbour's (1972), "*Turtles of the United States and Canada*". Their book established a new format with consistent species accounts that read less like narratives and more like ordered, complete summaries of knowledge. That edition was followed by two more versions including Ernst et al.'s (1994), "*Turtles of the United States and Canada*", and more recently, Ernst and Lovich's (2009), "*Turtles of the United States and Canada, Second Edition*". These five books are the basis for the data presented herein and each attempted to be a complete synthesis of knowledge at the time they were written. However, most comparisons were between the latter two due to similarities in organizational format, authorship, and taxonomy relative to earlier books. Using published summaries based on these books allows assessment based on static compilations of knowledge for the region of interest. This is in contrast to using various bibliographic sources on the internet that often change on a daily basis.

We used three basic knowledge indices to measure or approximate knowledge in our analyses. First, we counted the number of citations from each book (NCB), except for Pope (1939) who states that he consulted 800 "technical articles and books" before presenting a bibliography of selected references. Second, we counted the number of citations for each species (NCS) from the senior author's bibliographic database (ProCite© 4.0.3), compiled over more than 30 years of research on turtles. All citations in Ernst et al. (1994) and most of those in Ernst and Lovich (2009) are contained in the database (over 6000 citations, including a small number for topics not counted in this analysis such as citations for turtle species outside North America and titles unrelated to turtles). To count the number of citations for a particular turtle species we generated a species-specific search string and submitted it in the search engine in the bibliographic database. We used cutoff or publication dates shown in table 1 to submit search strings for various time intervals. The vast majority of citations in the database are comprised of peer-reviewed scientific journal articles, book chapters and proceedings chapters, although a small amount of gray literature is included. Our searches generated estimates per species that closely correspond to the actual number of citations in a particular chapter but are not always an exact match. As an extreme example, the account for *Kinosternon arizonense* (Arizona mud turtle) in Ernst and Lovich (2009) contains 17 actual citations while our NCS for the same species is only four. Much of this discrepancy is related to the fact that *K. arizonense* was once recognized as a subspecies of *Kinosternon flavescens* (yellow mud turtle). Searches of the database would yield fewer citations for *K. arizonense* than actually appeared since the literature for *K.*

arizonense is intermingled with citations for *K. flavescens*. Also, the search strings are slightly biased toward citations that contain a species name in the title, although the vast majority of records in the database are also indexed on keywords that contain specific epithets. As such, NCS values are themselves estimates of the actual number of citations per species account. It should also be noted that citations are not always independent. If a given publication contains information on more than one turtle species, it would be counted once for each species. Despite these limitations, counting citations as a knowledge index is not novel since it was previously used as a research tool by Adair and Vohra (2003) and specifically for turtles by Fitzsimmons and Hart (2007) and Lindeman (in press).

We used similar search strings to estimate the number of citations per genus (NCG). Since some genera are more speciose than others we divided the NCG values for each genus by the number of species within that genus to obtain a mean number of citations per species within a genus (MNCSWG).

The third metric we used as a knowledge index was the amount of text written for each species account in Ernst et al. (1994) and Ernst and Lovich (2009) measured in cm to the nearest 0.1 cm. Since these books were published in two-column format, we measured each column on every page and summed the values for all pages of a species account. We did not include the title of each account but did include spaces between paragraphs in the measurements. Measuring text to estimate accumulated knowledge was also used by Christoffel and Lepczyk (2012) for amphibians and reptiles and Lindeman (in press) for map turtles (*Graptemys*).

To characterize the dispersion of knowledge from 1994 to 2009, we calculated Shannon-Weiner diversity indices to compare the distribution (evenness) of citations among species. Also, we conducted a linear regression using $\log_{10}$ transformed NCS values for each species from 1994 and post-1994 to calculate a slope and determine the rate of accretion in citations over that time interval. Finally, we compare the increase of knowledge for two well-studied species, one protected under the ESA and the other a common and unprotected species.

To assess how conservation status may influence the acquisition of turtle knowledge, we used the IUCN Red List status taken from http://www.iucnredlist.org/ (accessed on 10 June, 2010) and U.S. Endangered Species Act (ESA) listings of the 56 species of turtles listed in Ernst and Lovich (2009). IUCN categories were assigned integer values of 3 through 0, so that lower numbers indicate a less imperiled status. For example, critically endangered was assigned as a 3, endangered as a 2, vulnerable as a 1, and not listed, lower risk/least concern, and lower risk/near threatened collectively as a 0. Spearman Rank correlation was then used to test the relationship between IUCN status and the rank of species from those with the lowest to the highest NCS in Ernst and Lovich (2009). The null hypothesis tested was that imperiled status was unrelated to species rank based on NCS. In addition, we compared the mean number of NCS values from Ernst and Lovich (2009) for all IUCN listed species against the mean for those species that were not listed using a Mann-Whitney U test. We made the same comparison for species listed as threatened or endangered under the U.S. Endangered Species Act (ESA) in any portion of their range vs. those that were not listed as such. To assess the effect of the amount of time (i.e., number of days) an ESA species has been listed on the acquisition of knowledge, we calculated the number of days since ESA listing and used a Spearman's rank correlation with this variable and NCS in Ernst and Lovich (2009), excluding non-listed species.

We also used maximum size values (carapace length = CL) from Ernst and Lovich (2009) and estimates of species' ranges from Buhlmann et al. (2009) to examine their relationship to NCS values. The latter did not include values for sea turtles. Taxonomic differences existed between Buhlmann et al. (2009) and Ernst and Lovich (2009), where Buhlmann et al. (2009) included *Chrysemys dorsalis* (southern painted turtle), *Graptemys sabinensis* (Sabine map turtle) and *Pseudemys floridana* (Florida cooter). These species were considered subspecies by Ernst and Lovich (2009), so their estimated ranges were included in the ranges of *Chrysemys picta* (painted turtle), *Graptemys ouachitensis* (Ouachita map turtle), and *Pseudemys concinna* (river cooter) for our analysis.

Statistical procedures were conducted using Systat 12, and Excel. When data were found to depart from normality based on visual examination of normal probability plots, they were transformed or nonparametric techniques were used, as appropriate. Levels of statistical significance were set *a priori* at an alpha of 0.05. Taxonomy follows Ernst and Lovich (2009) with recognition of minor changes from Ernst et al. (1994) as shown in the Appendix. Ennen et al. (2010) recently split *Graptemys gibbonsi* (Pascagoula map turtle) into two species, including *Graptemys pearlenis* (Pearl map turtle). The new taxon is not included in our analyses since only one paper, the description, has been published with that name combination. Similarly, our figures for *Gopherus agassizii* were generated before that species (*sensu lato*) was split to recognize *G. morafkai* (Murphy et al., 2011).

Results

NCB values on turtles of the United States and Canada have increased exponentially over time (table 1). Pope presented a relatively short bibliography of recommended citations but acknowledged that about 800 scientific sources were reviewed during the production of his book. The number cited by Carr (1952) is artificially higher than that cited by Ernst and Barbour (1972) since the latter used references primarily from 1950 to the end of 1970 and referred readers to Carr for earlier citations. The exponential rate of increase in citations is mirrored by the number of citations in the database for each decade from 1900-2000 (fig. 1).

Table 1. Attribute comparison of books written about turtles of the United States and Canada. Refer to text for details. Date for Pope based on 1961 printing while Carr is 1983 printing. The cut-off date refers to the approximate last year covered in the bibliography. Latter authors in particular included selected publications after the general cut-off date. Pope's bibliography includes selected citations out of 800 and Ernst and Barbour cite works primarily from 1950 to the end of 1970 since an unknown number of earlier references are contained in Carr.

	Publication				
	Pope	Carr	Ernst and Barbour	Ernst et al. (hard cover)	Ernst and Lovich
Publication date	1939	1952	1972	1994	2009
Cut-off date	unknown	unknown	1950-end of 1970	1 Oct., 1992	end of 2006
Page format	1 column, 22 × 15 cm	1 column, 23.5 × 16 cm	2 column, 26.5 × 21.5 cm	2 column, 25 × 17.5 cm	2 column, 28 × 21.5 cm
Total Arabic numbered pages	343	542	347	578	827
Pages in bibliography	12	68.2	47	88.1	170.4
Number of citations	800	1385	1286	2894	5241
(% change from previous)		(73.1%)	(−7.1%)	(125.0%)	(81.1%)

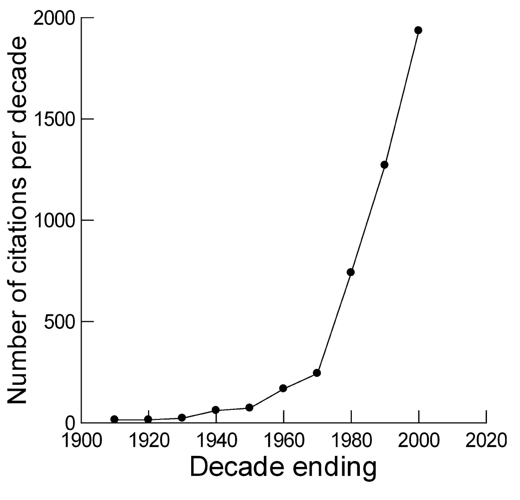

Figure 1. Estimated number of citations per decade (1900-2000) for all citations in the bibliographic database. Numbers are not cumulative. Points are connected for reference.

NCG values in 1994 ranged from 6 (*Palea* an established non-native species) to 261 (*Gopherus*) with a mean of 141.2 (sd = 60.1). The three best studied genera were *Chrysemys* (189), *Trachemys* (200), and *Gopherus* (261). By 2009, NCG values were still lowest for *Palea* (22) and highest for *Gopherus* (613) with a mean of 303.5 (sd = 145.1). The top three genera were *Chelonia* (396), *Trachemys* (433) and *Gopherus* (613). The lowest NCG values in 1994 were for *Palea* (6), *Pelodiscus* [another established non-native species] (10) and *Actinemys* (33). For 2009 the lowest values were seen in *Palea* (22), *Pelodiscus* (39) and *Deirochelys* (63). Within a genus (MNCSWG) results are shown in fig. 2. Rank change between 1994 and 2009 ranged from +5 to −3 but did not appear to be related to MNCSWG status within a genus as seen in fig. 2. Spearman rank correlations between the number of species in a genus and the number of citations in a genus in 1994 (r_s = 0.086, P = 0.10) and 2009 (r_s = 0.02, P = 0.18) were not significant. Genera containing only one species within the United States and Canada occupied the top five spots. Surprisingly, the speciose genera, *Graptemys* and *Pseudemys*, exhibited the lowest MNCSWG within a genus.

The NCS from Ernst et al. (1994) ranged from 1 (*Pseudemys gorzugi* [Rio Grande cooter]) to 198 (*Trachemys scripta* [pond slider]) with a mean of 45.2 (sd = 49.8). For Ernst and Lovich (2009) the NCS ranged from 4 (*Kinosternon arizonense* [Arizona mud turtle]) to 425 (*T. scripta*) with a mean of 99.2 (sd = 111.9) (fig. 3). The relationship between NCS in 1994 and 2009 editions (both variables $\log_{10}$ transformed) was significant when tested via linear regression (R^2 = 0.766, F = 176.9, df = 1, 54, P < 0.001) and exhibited a slope of 0.87 but exhibited a slope of 1.2 based on raw data (fig. 4). Thus, citations per species in 2009 increased at a rate of 1.2 citations relative

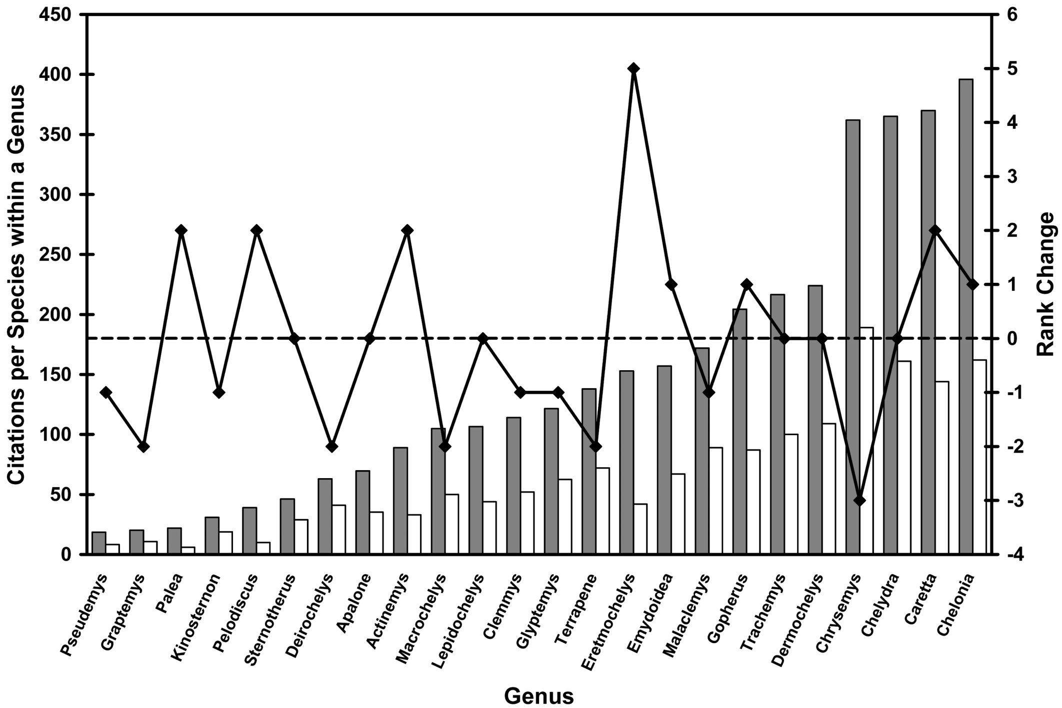

Figure 2. The mean number of citations for 1994 (open bars) and 2009 (shaded bars) per species within a turtle genus. The jagged line shows the change in rank order between 1994 and 2009.

to every one citation in 1994. The mean NCS for all species was significantly different between 1994 and 2009 editions (Mann-Whitney U test: $U = 1071.5$, df = 1, Chi-square approximation = 11.367, $P = 0.001$). The arithmetic difference in NCS between 1994 and 2009 editions ranged from 1 (*Kinosternon arizonense*) to 253 (*Gopherus agassizii* [desert tortoise]) citations with a mean of 53 citations (sd = 63.9). The percent change in NCS between 1994 and 2009 editions ranged from 26.7 (*Sternotherus depressus* [flattened musk turtle]) to 600% (*Pseudemys gorzugi* [Rio Grande cooter]) with a mean of 142.4% (sd = 92.6).

The amount of text per species in Ernst and Lovich (2009) ranged from 63.1 (*Pseudemys gorzugi*) to 1340.1 (*Gopherus agassizii*) cm with a mean of 345.8 cm (sd = 293.1). Using data from Ernst and Lovich (2009), the amount of text per species was highly correlated with NCS ($r = 0.94$) after $\log_{10}$ transformation of both variables to meet the assumption of normality. The transformed NCS explained 87.8% of the variation in transformed cm of text per species (fig. 5), and the relationship was statistically significant as shown by linear regression ($F = 401.2$, df = 1, 56, $P < 0.001$).

Plotting NCS in rank order shows three "natural" groupings: a "supergroup" of extremely well-studied species comprised of *Trachemys scripta*, *Gopherus agassizii*, *Chelonia mydas* (green seaturtle), *Caretta caretta* (loggerhead seaturtle), *Chelydra serpentina* (snapping turtle), and *Chrysemys picta* [painted turtle] (fig. 3). A second well-studied group contains *Dermochelys coriacea* (leatherback seaturtle), *Gopherus polyphemus* (gopher tortoise), and *Terrapene carolina* (eastern box turtle). All other species have fewer citations than these, some substantially so. The bottom ten, most poorly-studied species include: *Kinosternon arizonense*, *Pseudemys gorzugi*, *Kinosternon hirtipes* (rough-footed mud turtle), *Pseudemys peninsularis* (peninsula cooter), *Pseude-*

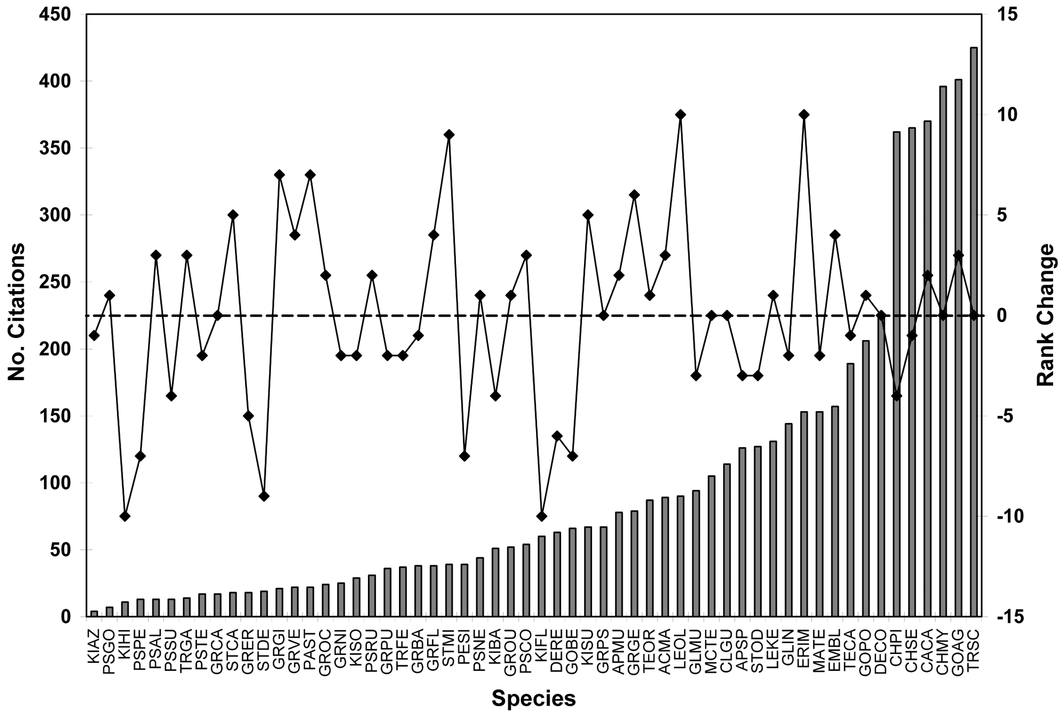

Figure 3. Estimated number of citations per species based on Ernst and Lovich (2009). Species abbreviations are shown in Appendix 1. Rank change from Ernst et al. (1994) is shown by the jagged line. Points connected for reference.

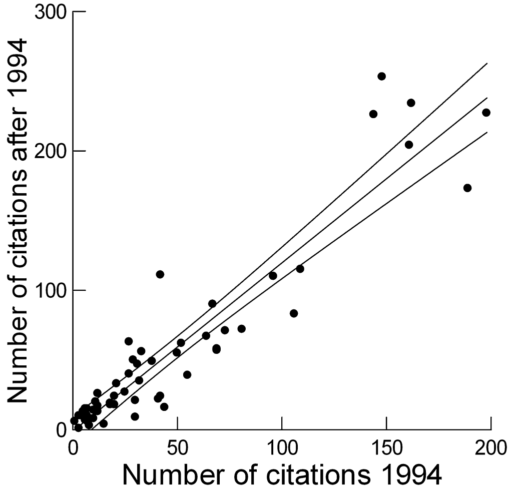

Figure 4. Relationship between number of citations per species from the database based on Ernst et al. (1994) and Ernst and Lovich (2009). A linear smoother is fitted to the data along with the 95% confidence interval. Note the difference in scales between X and Y axes. Refer to text for details.

mys alabamensis (Alabama red-bellied cooter), *Pseudemys suwanniensis* (Suwannee cooter), *Trachemys gaigeae* (Big Bend slider), *Pseudemys texana* (Texas river cooter), *Graptemys caglei* (Cagle's map turtle), and *Sternotherus carinatus* (Razor-backed musk turtle), ranging from 4-18 NCS. Even two long-established exotic species, *Palea steindachneri* (wattle-necked softshell) and *Pelodiscus sinensis* (Chinese softshell), rank higher than all the native species in the bottom ten, due mainly to studies in their natural range in Asia.

The Shannon Weiner diversity index measuring the diversity and evenness of NCS among species was 1.55 for both Ernst et al. (1994) and Ernst and Lovich (2009). Similarly Shannon Evenness Measures (J^1) were identical at 0.88.

Larger species and species with larger geographic ranges tended to have more citations. There was a significantly positive relationship between NCS for 2009 and maximum carapace length of the various turtle species based on linear regression (log/log transformed to meet

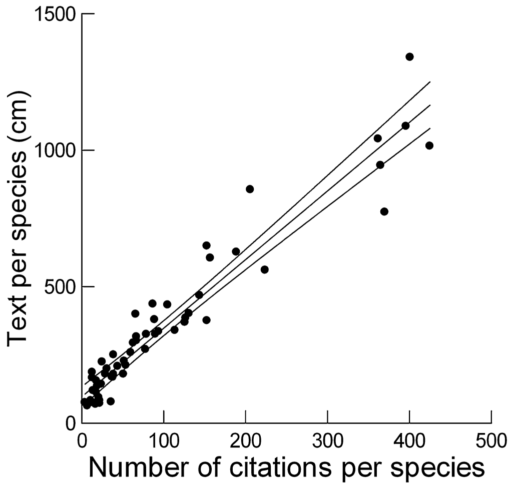

Figure 5. Relationship between estimated number of citations per species and cm of text per species based on data from Ernst and Lovich (2009). A linear smoother is fitted to the data along with the 95% confidence interval. Refer to text for details.

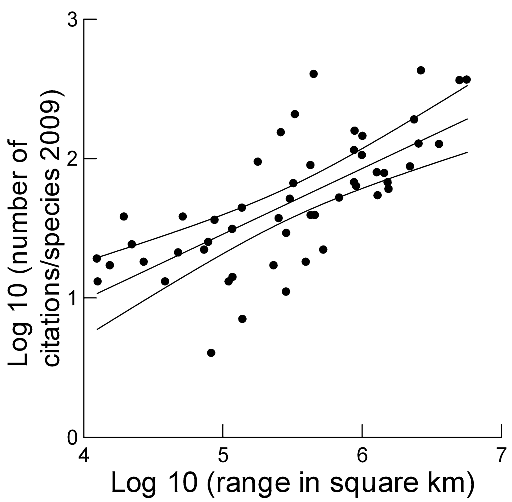

Figure 6. Relationship between log transformed species' range (km^2) and number of citations per species in 2009.

the assumptions of normality: $R^2 = 0.129$; F = 8.30; df = 1, 56; $P = 0.006$). Similarly there was a strong positive relationship between NCS for 2009 and range in km^2 (log/log transformed to meet the assumptions of normality: $R^2 = 0.506$; F = 51.17; df = 1, 50; $P < 0.001$) as shown in fig. 6.

The Spearman rank correlation coefficient between IUCN status and NCS based on Ernst and Lovich (2009) was positive ($r_s = 0.21$). That is, less imperiled species tended to have fewer citations than more imperiled species but the relationship was not statistically significant ($P = 0.11$). When comparing the mean NCS from Ernst and Lovich (2009) for both IUCN listed species (mean = 124.2) vs. those that were not listed (mean = 83.9) the difference was not significant (Mann-Whitney U test: $U = 307.5$, df = 1, Chi-square approximation = 2.01, $P = 0.16$). Comparing the same means for species listed under the ESA as threatened or endangered (mean = 156.4) vs. those that were not listed (mean = 81.0) demonstrated a marginally insignificant difference (Mann-Whitney U test: $U = 204.0$, df = 1, Chi-square approximation = 3.57, $P = 0.06$). However when the effect of CL was removed by using residuals from a linear regression between 2009 NCS and CL (both $\log_{10}$ transformed), the marginally insignificant result between ESA species and non-listed species was still insignificant (t-Test: t-Ratio = 0.87, df = 56, $P = 0.39$).

The rank change for individual species between 1994 and 2009 was significantly correlated with IUCN status ($r_s = 0.26$, $P = 0.05$), and rank change was significantly different (Mann-Whitney U test: $U = 200.5$, df = 1, Chi-square approximation = 3.84, $P = 0.05$) between ESA-listed species (1.86) and non-listed species (−0.59). However when the influence of CL and range were removed from the analyses by using the residuals from the linear regressions ($\log_{10}$[NCS] vs. $\log_{10}$[CL] and $\log_{10}$[range]), there was no significant relationship between IUCN status and rank change (CL: $r_s = 0.18$, $P = 0.18$; Range: $r_s = 0.17$, $P = 0.24$). Similarly with the removal of the influences of CL and range, rank change was not significantly different between ESA-listed species and non-listed species (CL: t-Test: t-Ratio = 1.09, df = 56, $P = 0.28$; Range: t-Ratio = 0.59, df = 50, $P = 0.55$). The amount of time ESA-listed species spent on the ESA roster was not significantly correlated with NCS in 2009 ($r_s = 0.43$, $P = 0.12$). Comparing the percent-

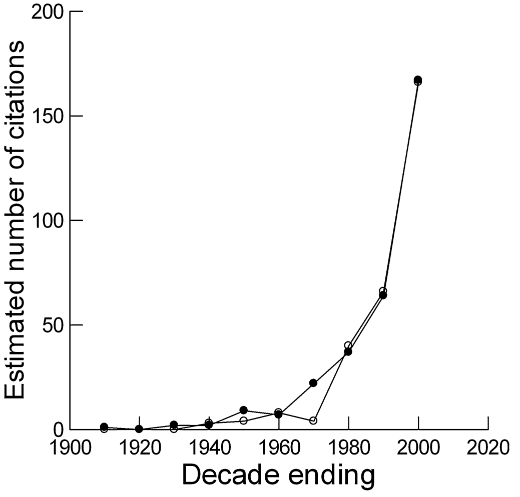

Figure 7. Relationship between estimated number of citations per decade for *Gopherus agassizii* (open circles) and *Trachemys scripta* (filled circles) based on data from Ernst and Lovich (2009). Numbers are not cumulative. Points are connected for reference.

age of species within a genus listed as protected with MNCSWG for 2009 was not significant for IUCN ($r_s = 0.01$, $P = 0.95$) or for ESA ($r_s = 0.27$, $P = 0.21$).

The two best-studied species, *Trachemys scripta* and *Gopherus agassizii* (*sensu lato*), provide a comparison in accretion of knowledge since the former is common and the latter is protected as a threatened species. Despite this difference, both increased at essentially the same rate over the same time period (fig. 7).

Discussion

Despite taxonomic bias in publication success against ectotherms, in particular amphibians and reptiles (Bonnet et al., 2002; Christoffel and Lepczyk, 2012), knowledge indices for turtles in the United States and Canada have increased exponentially in the recent century (fig. 1). We know vastly more about turtles of the United States and Canada than at any previous time in history. This is reflected both by an increase in the number of available citations/species (fig. 4) and a dramatic increase in text/species, especially looking at differences in page length between 1994 and 2009 (table 1). The strong correlation between amount of text and number of citations suggests that NCS is a strong determinant of text length with only a small amount of unexplained variance due to differences in writing style, verbosity, font style/size, spacing, kerning, or random error.

Since one of the definitions of knowledge we reviewed above was a defensible belief that increases capacity for effective action and problem solving (e.g., conservation and management plans for wildlife), a logical question is how this exponential increase in knowledge has been translated into effective action to conserve turtles? This is especially pertinent given the increasingly imperiled status of turtles (Gibbons et al., 2000; Klemens, 2000), and the answer seems to be, not always very well. For example, no ESA-listed species of tortoise or freshwater turtle in the United States and Canada has ever been delisted, suggesting that the explosive increase in turtle knowledge indices we examined do not translate into species recovery.

Interestingly, conservation status did not appear to be an influential driver for the increase in turtle knowledge indices as expected, especially considering that the ESA is one of the most stringent environmental laws in the world. One possible explanation for this scenario is that it is difficult to work with imperiled species due to small and declining population sizes and permit restrictions. For example, in our own research on *G. agassizii* (Lovich et al., 2011), a threatened species under ESA, we are required to have federal permits from the U.S. Fish and Wildlife Service and the Bureau of Land Management, in addition to a permit from the California Department of Fish and Game, and institutional animal care and use certification. Each permit requires adherence to stringent regulations and guidelines to ensure the well-being of the species. Successfully obtaining and keeping these permits requires demonstrated experience or training and compliance with the many guidelines. Given the potentially onerous requirements, it is possible that many researchers choose to study more common species with fewer restrictions. This could explain the apparent lack of relationship between conservation status and knowledge metrics.

However in the realm of conservation, particular biases have been shown to occur that influence public perception, ESA listing, and available funding (Metrick and Weitzman, 1998). Most notably is the taxonomic and size bias, where charismatic megafauna and birds were positively related to ESA listing and public funding for conservation more so than reptiles and other taxonomic groups (Metrick and Weitzman, 1998). Several of the analyses suggested that ESA and/or IUCN status had some influence on the accretion of knowledge. For example, rank change from 1994 to 2009 was influenced by ESA and IUCN status, and NCS was nearly influenced by ESA status. However when the effect of CL and/or range was removed, all the analyses were insignificant. Similarly, all other analyses showed no significant relationships between ESA and IUCN status and increase in knowledge indices. The insignificant result for analyses using IUCN status is not unexpected. As noted previously by Webb and Carrillo (2000), "*The incorrect listing of species could reflect errors in the IUCN criteria, a failure to distinguish between national and global status, or the failure of assessors to use the criteria properly or objectively.*"

The lack of strong relationships between ESA status and our measures of knowledge are noteworthy. For example *Sternotherus depressus*, a federally-threatened species under ESA, showed the lowest percent change in NCS between 1994 and 2009. Furthermore, the bottom 10 most poorly–cited species contained another species protected under ESA as a threatened species, *Pseudemys alabamensis*. The lack of substantial accretion of knowledge of these two species appears to be attributed to the two biases we identified in turtle research: size and geographic range. Alternatively, translating knowledge into policy to solve environmental problems is not always done effectively. Interagency cooperation, strategic planning and finding ways to have scientists participate in policy development and implementation are recommendations for improving the effectiveness of federal agencies in the application of scientific knowledge (Pouyat et al., 2010).

Another acknowledged bias in conservation is the trend toward more resources and ESA listings of larger species (Metrick and Weitzman, 1998). Similarly, turtles of the United States and Canada showed an identical trend, where larger turtle species have significantly more citations relative to smaller species. For example, seven of the top 10 species with the greatest NCS values were medium to large species (>30 cm; *Trachemys scripta*, *Gopherus agassizii*, *Chelydra serpentina*, *Chelonia mydas*, *Caretta caretta*, *Dermochelys coriacea*, and *Gopherus polyphemus*). This research bias towards larger species of turtles was undoubtedly influenced by the seven species of sea turtles. When sea turtles are removed from the regression analysis, the relationship between size and NCS disappears ($R^2 = 0.005$; F = 0.260; df = 1, 50; $P = 0.613$). Interestingly, ESA-listed turtle species were generally larger in size than non-listed species (Mann-Whitney U Test Statistic; 189.500; Chi-square Approximation = 4.64; df = 1; $P = 0.03$) suggesting that larger turtles species potentially are more vulnerable to population declines and anthropogenic perturbations. However, the two smallest species, *Glyptemys muhlenburgii* ([bog turtle]11.5 mm) and *Sternotherus depressus* (12.5 mm), in the United States and Canada are also federally listed. The size bias could explain the lack of citations for *S. depressus* but *G. muhlenburgii* has a relatively large literature.

Our analyses revealed another bias in the accretion of turtle knowledge, range size. Excluding the six 6 sea turtle species, there was a general trend for species with larger ranges to have more citations (NCS). Larger ranges could provide more opportunities for research and therefore more publications due the quantity of researchers in or near the range compared to turtles with smaller ranges. This phenomenon could explain the lack of citations for the two previously mentioned ESA-listed species, *Sternotherus depressus* (12 528 km^2) and *Pseudemys alabamensis* (12 712 km^2), where both species have the smallest ranges of any turtle in the United States and Canada. Also, five species (*Pseudemys alabamensis*, *Graptemys caglei*, *Graptemys ernsti* (Escambia map turtle), *Pseudemys suwanniensis*, and *Kinosternon arizonense*) out of the bottom ten in NCS had estimated ranges of less than 100 000 km^2 while seven species (*Trachemys scripta*, *Chelydra serpentina*, *Chrysemys picta*, *Terrapene carolina*, *Emydoidea blandingii* [Blanding's turtle], *Glyptemys insculpta* [wood turtle], and *Sternotherus odoratus* [common musk turtle]) out of the top ten species (excluding sea turtles) in NCS had an estimated range greater than 500 000 km^2.

The two best-studied species, *Trachemys scripta* and *Gopherus agassizii*, provide an interesting comparison (fig. 7). The former is an abundant species that has been introduced all over the world and is considered an invasive pest in many countries. The latter is a declining species that is protected as a threatened species under the ESA (Ernst and Lovich, 2009). The former is well-studied (e.g., Gibbons, 1990) due to the fact that it is common, easily trapped and marked (Gibbons, 1988), and hardy when maintained in laboratory settings. Studies of the latter were fueled by its final listing as threatened under the ESA in 1990. According to the U.S. Government Accountability Office (2002), more than \$100 million has been spent on *G. agassizii* recovery actions (including research) since the species was first listed in 1980 (the Beaver Dam Slope population in Utah was listed as threatened at that time). Between 1980 and present we estimate that 363 citations were published for *G. agassizii*. That translates into an estimated cost of \$275 482 for each publication if recovery actions are strongly related to application of research results! Knowledge is not cheap when it comes to turtle research and this underscores the importance of using it to solve conservation problems effectively. Still, the massive expenditure has not resulted in the delisting of any *G. agassizii* populations. In fact, no turtle species protected under the ESA has ever been delisted for reason of recovery (U.S. Fish and Wildlife Service, 2013: http://ecos.fws.gov/tess_public/DelistingReport.do), nor has any CITES-listed turtle species (B. Weissgold, pers. comm.).

Management implications

Significant knowledge biases highlighted in this paper underscore the need to focus research on the understudied turtles identified in our analysis, especially ESA-listed species. For example, *Sternotherus depressus* and *Pseudemys alabamensis* have been federally listed since 1987, but both species have NCS values less than 20 citations! Another federally listed species, *Graptemys oculifera*, has been listed since 1986 but only has an NCS value of 24 citations. In comparison, *Gopherus polyphemus* was listed approximately at the same time as S. *depressus*, *P. alabamensis*, and *G. oculifera* but has an NCS value of 206. It is hoped that the identification of poorly-studied species in this paper will spur further research on those taxa and that existing and future knowledge will be utilized to more effectively implement conservation actions to benefit turtle populations in the United States and Canada. However, there appears to be a potential disconnect between the amount of knowledge available and species recovery and delisting. The techniques used in this study could be used in similar analyses for other groups of organisms as an assessment tool for both knowledge and its translation into conservation effectiveness.

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Appendix. The 58 recognized species, as in Ernst and Lovich (2009), of United States and Canada turtles in ranked order by number of citations with Ernst et al. (1994) taxonomy, species code, and common names. Rank is based on the number of papers published primarily through the end of 2006 (Ernst and Lovich, 2009).

Rank	Species	Ernst et al. (1994) taxonomy	Sp code	Common Name
1	*Trachemys scripta*	*Trachemys scripta*	TRSC	pond slider
2	*Gopherus agassizii*	*Gopherus agassizii*	GOAG	desert tortoise
3	*Chelonia mydas*	*Chelonia mydas*	CHMY	green seaturtle
4	*Caretta caretta*	*Caretta caretta*	CACA	loggerhead seaturtle
5	*Chelydra serpentina*	*Chelydra serpentina*	CHSE	snapping turtle
6	*Chrysemys picta*	*Chrysemys picta*	CHPI	painted turtle
7	*Dermochelys coriacea*	*Dermochelys coriacea*	DECO	leatherback seaturtle
8	*Gopherus polyphemus*	*Gopherus polyphemus*	GOPO	gopher tortoise
9	*Terrapene carolina*	*Terrapene carolina*	TECA	eastern box turtle
10	*Emydoidea blandingii*	*Emydoidea blandingii*	EMBL	Blanding's turtle
11	*Malaclemys terrapin*	*Malaclemys terrapin*	MATE	diamond-backed terrapin
12	*Eretmochelys imbricata*	*Eretmochelys imbricata*	ERIM	hawksbill seaturtle
13	*Glyptemys insculpta*	*Clemmys insculpta*	GLIN	wood turtle
14	*Lepidochelys kempii*	*Lepidochelys kempii*	LEKE	Kemp's Ridley seaturtle
15	*Sternotherus odoratus*	*Sternotherus odoratus*	STOD	common musk turtle
16	*Apalone spinifera*	*Trionyx spiniferus*	APSP	spiny softshell
17	*Clemmys guttata*	*Clemmys guttata*	CLGU	spotted turtle
18	*Macrochelys temminckii*	*Macroclemys temminckii*	MCTE	allligator snapping turtle
19	*Glyptemys muhlenbergii*	*Clemmys muhlenbergii*	GLMU	bog turtle
20	*Lepidochelys olivacea*	*Lepidochelys olivacea*	LEOL	olive ridley seaturtle
21	*Actinemys marmorata*	*Clemmys marmorata*	ACMA	Pacific pond turtle
22	*Terrapene ornata*	*Terrapene ornata*	TEOR	ornate box turtle
23	*Graptemys geographica*	*Graptemys geographica*	GRGE	Northern map turtle
24	*Apalone mutica*	*Trionyx muticus*	APMU	smooth softshell
25	*Graptemys pseudogeographica*	*Graptemys pseudogeographica*	GRPS	false map turtle
26	*Kinosternon subrubrum*	*Kinosternon subrubrum*	KISU	Eastern mud turtle
27	*Gopherus berlandieri*	*Gopherus berlandieri*	GOBE	Berlandier's tortoise
28	*Deirochelys reticularia*	*Deirochelys reticularia*	DERE	chicken turtle
29	*Kinosternon flavescens*	*Kinosternon flavescens*	KIFL	yellow mud turtle
30	*Pseudemys concinna*	*Pseudemys concinna*	PSCO	river cooter
31	*Graptemys ouachitensis*	*Graptemys ouachitensis*	GROU	Ouachita map turtle
32	*Kinosternon baurii*	*Kinosternon baurii*	KIBA	striped mud turtle
33	*Pseudemys nelsoni*	*Pseudemys nelsoni*	PSNE	Florida red-bellied cooter
34	*Pelodiscus sinensis*	*Trionyx sinensis*	PESI	Chinese softshell
35	*Sternotherus minor*	*Sternotherus minor*	STMI	loggerhead musk turtle
36	*Graptemys flavimaculata*	*Graptemys flavimaculata*	GRFL	yellow-blotched map turtle
37	*Graptemys barbouri*	*Graptemys barbouri*	GRBA	Barbour's map turtle
38	*Apalone ferox*	*Trionyx ferox*	APFE	Florida softshell
39	*Graptemys pulchra*	*Graptemys pulchra*	GRPU	Alabama map turtle
40	*Pseudemys rubriventris*	*Pseudemys rubriventris*	PSRU	Northern red-bellied cooter
41	*Kinosternon sonoriense*	*Kinosternon sonoriense*	KISO	Sonora mud turtle
42	*Graptemys nigrinoda*	*Graptemys nigrinoda*	GRNI	black-knobbed map turtle
43	*Graptemys oculifera*	*Graptemys oculifera*	GROC	ringed map turtle
44	*Palea steindachneri*	*Trionyx steindachneri*	PAST	wattle-necked softshell
45	*Graptemys versa*	*Graptemys versa*	GRVE	Texas map turtle
46	*Graptemys gibbonsi*	*Graptemys gibbonsi*	GRGI	Pascagoula map turtle
47	*Sternotherus depressus*	*Sternotherus depressus*	STDE	flattened musk turtle
48	*Graptemys ernsti*	*Graptemys ernsti*	GRER	Escambia map turtle
49	*Sternotherus carinatus*	*Sternotherus carinatus*	STCA	razor-backed musk turtle
50	*Graptemys caglei*	*Graptemys caglei*	GRCA	Cagle's map turtle
51	*Pseudemys texana*	*Pseudemys texana*	PSTE	Texas river cooter
52	*Trachemys gaigeae*	*Trachemys gaigeae*	TRGA	Big Bend slider
53	*Pseudemys suwanniensis*	*Pseudemys concinna suwanniensis*	PSSU	Suwannee cooter

Appendix. (Continued.)

Rank	Species	Ernst et al. (1994) taxonomy	Sp code	Common Name
54	*Pseudemys alabamensis*	*Pseudemys alabamensis*	PSAL	Alabama red-bellied cooter
55	*Pseudemys peninsularis*	*Pseudemys floridana peninsularis*	PSPE	peninsula cooter
56	*Kinosternon hirtipes*	*Kinosternon hirtipes*	KIHI	rough-footed mud turtle
57	*Pseudemys gorzugi*	*Pseudemys gorzugi*	PSGO	Rio Grande cooter
58	*Kinosternon arizonense*	*Kinosternon flavescens arizonense*	KIAZ	Arizona mud turtle