Global Disparity in Public Awareness of the Biological Control Potential of Invertebrates

Kris A.G. Wyckhuys[1,2,3,4*], Gabor Pozsgai[4], Gabor L. Lovei[4,5], Liette Vasseur[4,6], Steve D. Wratten[4,7], Geoff M. Gurr[4,8], Olivia L. Reynolds[4,8,9], Mark Goettel[4,10]

1. University of Queensland, Brisbane, Australia
2. China Academy of Agricultural Sciences, Beijing, China
3. Zhejiang University, Hangzhou, China
4. International Joint Research Laboratory on Ecological Pest Management, Fuzhou, China
5. Aarhus University, Slagelse, Denmark
6. Brock University, St. Catharines, Ontario, Canada
7. Lincoln University, Lincoln, New Zealand
8. Graham Centre for Agricultural Innovation, Wagga Wagga, Australia
9. New South Wales Department of Primary Industries, Narellan, Australia
10. Lethbridge Research Centre, Agriculture & Agri-Food Canada

Corresponding author:

Kris A.G. Wyckhuys
Institute of Plant Protection,
Chinese Academy of Agricultural Sciences,
No. 2 West Yuanmingyuan Rd., Haidian District,
Beijing, 100193, P. R. China
Tel: 86-10-62813685
Contact: kagwyckhuys@gmail.com

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Abstract

Invertebrates make up 97-99% of biodiversity on Earth and contribute to multiple ecosystem services (ES) in both natural and human-dominated systems. One such service, biological control (BC) of herbivorous pests, is a core component of sustainable intensification of agriculture, yet its importance is routinely overlooked. Here we report a macro-scale, cross-cultural assessment of the public visibility (or 'awareness') of BC invertebrates, using high-throughput analysis of large bodies of digitized text. Using binomial scientific name frequency as proxy for awareness, we compared the extent to which a given species featured in webpages within either scientific media or the entire worldwide web, and in total search volume at varying spatial scale. For a set of 339 BC invertebrate species, scientific and internet coverage averaged 1,020 and 1,735 webpages, respectively. Substantial variability was recorded among BC taxa with Coleoptera, Hemiptera and Nematoda having comparatively high visibility. Online visibility exhibited large geographical variability ranging from France covering BC invertebrates on average in 1,050 webpages versus USA on just 31. This work represents the first extensive use of culturomics to assess public visibility of insect-mediated ES. As BC uptake is dictated by stakeholders' access to (agro-ecological) information, our work identifies geographically-delineated areas that are differentially attuned to the concept of invertebrate BC, pinpoints opportunities for focusing education campaigns and awareness-raising, enables real-time tracking of BC public appeal, and informs public policy.

Keywords: agro-ecology; ecological intensification; functional biodiversity; ecosystem services; pest management; computational science; public perception ; Big Data

Introduction

Biological control (BC), the suppression of vertebrate and invertebrate pests, weeds or plant pathogens by living organisms through competition, herbivory, parasitism or predation features as an important ecosystem service (ES) worldwide. Conservatively valued at US \$63 ha^{-1} y^{-1} across global biota, biological pest control is of critical importance to the sound functioning of terrestrial and aquatic ecosystems world-wide (Costanza et al., 2014). Estimated to be worth between \$4.5-17 billion annually to US agriculture alone (Losey & Vaughan, 2006), insect-mediated biological control is progressively recognized as a core component of sustainable intensification schemes and regenerative farming tactics (Tscharntke et al., 2012; Bommarco et al., 2013; Garibaldi et al., 2017; La Canne & Lundgren, 2018). Considered an environmentally-benign alternative to pesticide use, scientifically-underpinned BC supports a profitable production of healthy, nutritious agricultural produce from biologically-diverse farming systems.

Though BC has been used by growers for over 2000 years, with the oldest example being the manipulation of *Oecophylla* spp. weaver ants for pest control in Asian citrus orchards (Chen, 1962), its modern application dates back to the late 1800s (De Bach & Rosen, 1991). There are different types of BC approaches including importation BC (i.e., inoculative releases of carefully-selected exotic agents) and conservation BC (i.e., promotion of native and naturalized agents). A third type of BC (i.e., augmentative biological control; ABC) uses mass-production, shipment, and subsequent field release of biological control agents, and is implemented on approx. 10% of the world’s agricultural land, primarily in protected cultivation but also in field crops such as corn, sugarcane, cotton and silviculture (van Lenteren & Bueno, 2003; Heimpel & Mills, 2017). ABC relies upon a comparatively high degree of involvement from various stakeholders, including farmers, government actors and private enterprises (Bale et al., 2008), and so is more likely to be known to sectors of the general public than other BC approaches that may be implemented by agencies and tend to require less farmer participation (Andrews et al., 1992).

At present, nearly 350 invertebrate natural enemy species are available for augmentative BC use in agriculture globally (van Lenteren, 2012; van Lenteren et al., 2018). Yet, despite the extensive availability of (and access to) such organisms, uptake of augmentative BC proceeds at a 'frustratingly' slow pace (van Lenteren, 2012). Multiple factors hamper the farm-level adoption and diffusion of knowledge-intensive technologies such of biological control, including its in-field success rate (Collier & Van Steenwyk, 2004; Sivinski, 2013). However, the absence of sufficient publicly-accessible information and farmers' lagging knowledge may be one of the main obstacles (Pretty & Bharucha, 2014; Reganold & Wachter, 2016; Wyckhuys et al., 2018). This is further compounded by a misconception and general indifference towards invertebrates among the broader public (Hogue, 1987; Kellert, 1993; Lemelin et al., 2016), a decline in the number of biological control courses in core curricula at some academic institutions (Warner et al., 2011), and dwindling interest in this key ecosystem service across digitally-enabled groups of society such as 'generation Y' and 'millenials' (Brodeur et al., 2018).

To address these challenges, social science research can be deployed to conduct systematic broad-scale assessments of public perceptions and attitudes towards (beneficial) invertebrates, identify (farmer) knowledge gaps and help pinpoint associated opportunities for tailored extension or adult education (Wyckhuys & O'Neil, 2007). Yet, conventional social science approaches are increasingly constrained by declining survey response rates and lagging youth engagement (Sherren et al., 2017). On the other hand, considering how the internet currently permeates most levels of society, the digital humanities offer unparalleled opportunities to diagnose, map and track public interest in phenomena at a macro-scale (Galaz et al., 2010; McCallum & Bury, 2013; Proulx et al., 2014; Ladle et al., 2016). More specifically, the emerging field of 'culturomics' refers to the non-reactive, high-throughput collection, analysis and interpretation of large bodies of digitized text, or '*digital corpora*' (Michel et al., 2011). These approaches have readily been embraced by scholars in disciplines ranging from political science, linguistics to conservation biology, yet are still to be used to assess public perceptions of agro-ecology or biological control.

Globally, there are over one billion websites exist, with more than 333 million domain names registered across the top-level domains (TLDs), and approx. 5 billion queries submitted every day through Google search engines (Correia et al., 2017; Verisign, 2018). This expansive, ever growing *corpus* has been examined by various scholars, yielding novel insights into the determinants of public interest in climate change or specific ecosystem services (Anderegg & Goldsmith, 2014), and providing a powerful lens on human relations with the living world, including birds (Schuetz et al., 2015), fish (Stergiou, 2017) and butterflies (Zmihorski et al., 2013). In culturomics research, the (relative) number of websites that feature a particular species, or '*internet salience*', is a reflection of its public visibility, or '*culturalness*' (Correia et al., 2016). A species' scientific binomial name has been proposed as a robust metric to gauge its cultural visibility across linguistic, cultural or geographical boundaries (Correia et al., 2017). Public visibility can also be inferred by the number of search hits, as obtained through Google Trends, over a specific time frame (Schuetz et al., 2015; Do et al., 2015). Though this cultural visibility can be considered as a 'species trait' on its own, it is equally shaped by a species' phenotypic (e.g., body size) or biogeographic (e.g., commonness) characteristics, and public attitudes or beliefs that revolve around that species (Zmihorski et al., 2013; Correia et al., 2016; Kim et al., 2014). If their near-absence on postage stamps or under-representation on ‘Noah’s Ark’ iconography is reflective of the low ‘culturalness’ of insects and invertebrates (Price, 1988; Nemesio et al., 2013), this may at least partially preclude their deliberate use, manipulation and conservation as ES-providing organisms in sustainable agriculture globally.

In this study, we embarked upon a pioneering agro-ecology culturomics assessment and employed powerful text-mining tools to diagnose online public visibility of over 300 invertebrate biological control organisms. More specifically, we *i*) contrasted the degree to which a particular organism features in the scientific literature with its internet salience, at a global and country-specific level; *ii*) compared the culturalness of organisms belonging to different taxa, at a global and country-specific level; and *iii*) assessed the relative search volume of biological control organisms with differing levels of internet salience, at a global level and for the USA and UK specifically. Aside from providing a first comprehensive overview of global cultural interest in invertebrate biological control organisms (through a digital lens), our study points at opportunities for a tactical use of digital media analytics in the promotion of insect-mediated ecosystem services and their effective incorporation into sustainable agricultural intensification worldwide (Pretty et al., 2018).

Materials & Methods

This analysis focused on the listing of 339 invertebrate natural enemy species that are used in augmentative biological control (ABC) of insect pests globally (van Lenteren, 2012; van

Lenteren et al., 2018). These organisms covered eleven different groups: predatory mites (Acari; *n*= 51), predaceous beetles (Coleoptera; *n*= 40), true bugs (Hemiptera; *n*= 24), insect-killing flies (Diptera; *n*= 11), parasitic hymenopterans (Hymenoptera; *n*= 170), entomphagous nematodes (Nematoda; *n*= 11), lacewings (Neuroptera; *n*= 20), predaceous thrips (Thysanoptera; n= 7), praying mantids (Mantodea; *n*= 3), centipedes (Chilopoda; *n*= 1) and a predatory land snail (Mollusca; *n*= 1).

To run the queries, we used upon Google search engines as those currently represent >73% of the share of the global search engine market (NetMarketShare, 2018). All queries were run between May 24 and June 15, 2018, from Hanoi, Vietnam, using a Lenovo laptop computer with regular internet connection and Google Chrome browser. Google Chrome represents 62.7% of the world’s browser market (NetMarketShare, 2018). Using this set-up, we extracted data from the World Wide Web for each biological control species, at global and country-specific levels. All queries were run using binomial scientific names of a given species as quoted search strings (e.g., "*Propylaea japonica*"), thus restricting search returns to the exact match of the string. We exclusively conducted internet searches using scientific names (Correia et al., 2017), and did not correct for potential synonyms (Correia et al., 2018). For comparative purposes, we ran equivalent searches for species that might receive substantial public interest from aesthetic, human health or ES-delivery perspectives: the monarch butterfly *Danaus plexippus* (L.), the pollinators *Apis mellifera* L. and *Bombus terrestris* (L.), the virus-vectoring mosquitoes *Culex pipiens* L. and *Aedes aegypti* L., and the weaver ant *Oecophylla smaragdina* (Fabricius).

First, we used a Google Scholar (GS) interface to quantify the extent to which a given biological control organism features in the global scientific literature (Table 2). Despite considerable variability in the effectiveness of different search interfaces for library resources

(Asher et al., 2013), Google Scholar does outperform commercially-available engines (Ciccone & Vickery, 2015). Using similar reasoning as in Correia et al. (2016), we employed the number of GS results as a direct measure of the extent to which a given species is covered in scientific documents and thus a proxy of its global scientific attention, or '*scientific salience*' (SciS).

Second, we employed Google Custom Search to obtain organism-specific measures of '*internet salience'*, and to circumvent issues related to Google's personalization algorithms (Correia et al., 2016, 2017). A total of 11 different searches were carried out: one global search across all registered domains (as specified under editing mode at the Custom Search Engine platform), and a total of ten country-specific searches – for Brazil, France, Germany, Indonesia, Kenya, Russia, Tanzania, Thailand, United Kingdom (UK) and the United States of America (USA) (populous countries with variable rates of internet usage; Table 1). The latter searches were delimited by the respective country web domains (i.e., .br, .fr, .de, .id, .ke, .ru, .tz, .th, .uk, .us). Above searches were run exclusively using binomial scientific names, and no language preferences were set. The resulting output, the number of websites that feature a given biological control organism, was used as a proxy of its '*internet salience*' (IS) over a particular geographic area. IS metrics were computed as absolute values (i.e., total number of websites), and as relative values (i.e., proportion of websites within a given country-code domain, ccTLD). For purposes of data visualization, an additional metric was computed to reflect relative internet visibility, through *(IS-SciS)/SciS*.

Third, we employed the 'Keywords Everywhere' interface (Anonymous, 2018) to quantify online search behavior as related to each of the different biological control organisms. 'Keywords Everywhere' assesses consumer behavior and generates the total monthly searches that have been performed for a particular keyword over a 12-month time frame. The list of binomial scientific names was ‘bulk-uploaded’ as quoted search strings, and keyword metrics were generated for all websites (i.e., global extent) and those restricted to the UK and the USA (for which ‘Keywords Everywhere’ records are available). The above search volume thus constituted a quantitative metric of ‘*real-time public interest*’ for a specific biological control organism.

We conducted a linear regression analysis to relate organism-specific metrics of SciS and IS, either drawing upon the global dataset or country-specific records. Country-level analyses were also carried out accounting for local (commercial) availability of specific organisms, by excluding organisms that were locally not available (van Lenteren, 2012; van Lenteren et al., 2018). IS of individual biological control organisms either at the global or country-specific level was compared among taxa using a One-way Analysis of Variance (ANOVA), while a comparison of IS and SciS measures for a particular organism was done using a paired-samples *t-test*. Lastly, a linear regression analysis was conducted to relate organism-specific metrics of real-time public interest to IS measures for the global dataset and for the UK and USA based records (i.e., only countries from our list accessible through Keywords Everywhere). Where necessary and feasible, data were log-normal or rank-based inversed transformed to meet assumptions of normality and homoscedasticity, and all statistical analyses were conducted using SPSS (PASW Statistics 18).

Results

i. Scientific and internet salience

Web searches yielded on average 1,020 ± 1,772 (mean ± SD) scientific documents and 1,735 ± 5,487 public webpages per BC organism. For any given organism, the number of webpages was significantly higher than its respective number of scientific records (Paired samples Student's *t*-test, t= -8.390, df = 338, p< 0.001).

In terms of SciS, the five most featured organisms were *Coccinella septempunctata* Linnaeus (Coleoptera: Coccinellidae; 13,100 documents), *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae; 12,300), *Nasonia vitripennis* (Walker) (Hymenoptera: Pteromalidae, 10,000), *Chrysoperla carnea* Stephens (Neuroptera: Chrysopidae; 9,950) and *Phytoseiulus persimilis* Evans (Acari: Phytoseiidae; 8,990). The highest SciS for Diptera, Hemiptera, Mantodea and Nematoda were *Episyrphus balteatus* De Geer (4,090), *Orius insidiosus* (Say) (5,030), *Mantis religiosa* (Linnaeus) (4,050) and *Steinernema carpocapsae* (Weiser) (8,150), respectively. This compared to SciS metrics for the mosquitoes *A. aegypti* (212,000) and *C. pipiens* (45,100) and the honeybee *A. mellifera* (201,000). Overall, 95% of biological control organisms had SciS below 4,100 documents and 75% of them had less than 1,000 records per organism; 20.1% of biological control organisms featured on less than 100 scientific documents globally.

As for IS, the five most featured organisms were the praying mantis *M. religiosa* (83,200), *C. septempunctata* (33,600), *H. axyridis* (29,300), *P. persimilis* (15,400) and *C. carnea* (15,300). The highest IS measures for Diptera, Hemiptera, Hymenoptera and Nematoda were *E. balteatus* (11,700), *O. insidiosus* (6,200), *N. vitripennis* (10,700) and *S. carpocapsae* (10,500). The above compared to IS metrics of e.g., 961,000 for *A. aegypti*, 231,000 for *A. mellifera*, or 70,100 for *D. plexippus*. Overall, 95% of biological control organisms had IS less than 6,000 webpages and 80% more than 2,000 per organism; 17.6% of them featured on less than 100 webpages globally.

ii. Global and country-level relationship between scientific salience? and internet salience

At a global level, a significant positive regression was recorded between organism-specific SciS and IS measures ($F_{1,334}$= 2257.0, p< 0.001; R^2= 0.871) (Fig. 1). This same pattern was also confirmed for individual countries: Russia ($F_{1,334}$= 524.0, p< 0.001; R^2= 0.611), France ($F_{1,334}$= 469.9, p< 0.001; R^2= 0.585), USA ($F_{1,335}$= 722.6, p< 0.001; R^2= 0.683), Germany ($F_{1,334}$= 553.9, p< 0.001; R^2= 0.624), Brazil ($F_{1,334}$= 751.6, p< 0.001; R2= 0.692), Indonesia ($F_{1,334}$= 422.3, p< 0.001; R^2= 0.558), Thailand ($F_{1,334}$= 253.0, p< 0.001; R^2= 0.431), and Kenya ($F_{1,334}$= 284.3, p< 0.001; R^2= 0.460). Overall, the positive regression patterns were sustained when correcting for local (commercial) availability of individual organisms (based on continent-level records in 13, 14). More specifically, the following positive regressions were recorded: Russia ($F_{1,233}$= 415.3, p< 0.001; R^2= 0.641), France ($F_{1,204}$= 319.1, p< 0.001; R^2= 0.610), USA ($F_{1,94}$= 338.4, p< 0.001; R^2= 0.783), Germany ($F_{1,204}$= 359.5, p< 0.001; R^2= 0.638), Brazil ($F_{1,67}$= 108.1, p< 0.001; R^2= 0.617), Indonesia ($F_{1,50}$= 62.084, p< 0.001; R^2= 0.5584), Thailand ($F_{1,51}$= 24.397, p< 0.001; R^2= 0.324), and Kenya ($F_{1,29}$= 12.9, p= 0.001; R^2= 0.309).

Not all organisms featured to equal extent on webpages in the different countries, with 99% of the 339 biological control organisms being covered in Germany and the UK, 95% coverage in Brazil, 64% in Thailand and 38% in Kenya. Considerable between-country variability was recorded in the extent to which biological control species feature, with a mean of 1,050 (SD=5,100) webpages per species in France versus 167 (SD= 596), 31 (SD=120), 38 (SD=120) and 65 (SD=469) for Russia, USA, Indonesia and Kenya, respectively. In Tanzania, only 11 species featured on local sites with 1 ± 1 webpage per organism. France had significantly higher

IS measures for biological control species than e.g., USA or Russia, in both absolute (Paired samples Student's *t*-test, t= 22.132, df= 299, p< 0.001; t= 14.524, df= 308, p< 0.001, respectively) as relative numbers (t= 16.262, df= 299, p< 0.001; t= -23.236, df= 308, p< 0.001, respectively). As compared with France, IS of individual biological control organisms in e.g., Brazil was 9.14 ± 27.65 times lower (Fig. 1A, B). In certain countries such as Kenya, a mere 38.6% of biological control invertebrates featured on webpages in the country domain.

Significant regressions were equally obtained between organism-specific SciS and IS metrics, when assessing global patterns for each of the most representative taxa (see Table 3).

iii. Taxa-specific differences in internet salience

Organism-specific IS and SciS measures varied among the seven most representative natural enemy taxa (Table 3), with Nematoda attaining both the highest levels of scientific and internet salience. Out of the 11 nematode species that are used globally, seven had SciS >1,000 per organism and three species (i.e., *Steinernema feltiae* Filipjev, *Heterorhabitis bacteriophora* Poinar, and *S. carpocapsae*) attained SciS > 5,000. Hemiptera had comparatively high SciS and IS, whilst Coleoptera and Diptera equally received high levels of internet salience (though Diptera featured to lesser extent in scientific media).

On the country level, significant inter-taxa differences were recorded for IS of the six most representative taxa (Fig. 3) for Russia ($F_{5,310}$= 7.322, p< 0.001), Germany ($F_{5,309}$= 3.466, p= 0.005) and Indonesia ($F_{5,309}$= 2.585, p= 0.026). In France, 20% of Coleoptera featured on >1,000 webpages, with coccinellids such as *H. axyridis* (58,200), *C. septempunctata* (40,300), *Adalia bipunctata* L. (31,900), *Hippodamia variegata* (Goeze) (8,810) and *Exochomus quadripustulatus*

L. (4,810) most mentioned. When correcting for local (commercial) availability of biological control organisms, significant inter-taxa IS differences were evident for Russia ($F_{5,187}$= 8.735, p< 0.001), France ($F_{5,186}$= 3.157, p= 0.009) and Germany ($F_{5,186}$= 4.479, p= 0.001), while no statistically-significant inter-taxa IS differences were recorded for the other countries.

iv. Relationship between internet salience and real-time public interest

When assessing real-time public interest (as monthly 'hits' through 'Keywords Everywhere') in biological control organisms, only 41.0%, 39.8% and 40.7% of all species featured in searches at global, UK- and USA-specific levels. At these respective levels, biological control organisms received an average of 926.5 ± 5,297.7 (mean ± SD), 35.6 ± 142.8 and 121.2 ± 525.6 searches per month, respectively. Global search interest differed substantially among taxa, with search volume covering 20.0% (Neuroptera), 33.3% (Acari), 45.0% (Diptera), 45.4% (Coleoptera), and 90.9% Nematoda species.

The five species that received most monthly searches globally during the preceding year (i.e., 2017-2018) were *M. religiosa* (60,500), *H. axyridis* (14,800), *C. septempunctata* (8,100), *P. persimilis* (2,900) and *C. carnea* (2,400). In the UK, monthly search volume was the highest for *H. axyridis* (1,600), with *C. septempunctata* (390), *M. religiosa* (210), *P. persimilis* (170) and the whitefly parasitoid *Encarsia formosa* Gahan (140) following in ranked order. In the USA, a similar ranking for the five most popular organisms was obtained, with search volume ranging between 480 and 5,400, *H. axyridis* the most commonly searched organism, and *Hippodamia convergens* (Guërin-Mëneville) featuring instead of *C. carnea*.

For biological control organisms that featured in online searches, real-time public interest was significantly related to internet salience at a global, UK- and USA- specific level ($F_{1,136}$= 538.732, $p< 0.001$, R^2= 0.798; $F_{1,131}$= 102.581, $p< 0.001$, R^2= 0.439; $F_{1,133}$= 121.595, R^2= 0.478, respectively) (Fig.4).

Discussion

Combining powerful text-mining tools and culturomics approaches to assess the visibility of globally-relevant biological control invertebrates revealed how these organisms feature on average on 1,735 webpages globally, as compared to 34,700-231,000 for bee pollinators or 50,900-961,000 for prominent ecosystem-disservice providers (i.e., disease-carrying mosquitos). Coleoptera, Hemiptera and Nematoda demonstrated comparatively high public and scientific visibility. In contrast, Acari, Hymenoptera and Neuroptera were less apparent. Significant differences were also apparent among geographical domains, with France covering a given biological control organism on average in 1,050 webpages versus the USA, 31. Further, real-time public interest as reflected by search volume varied greatly between individual taxa and different countries, with charismatic ladybeetles and praying mantids dominating most public attention.

Internet salience (IS) of biological control species (entered as binomial scientific names) in our study is similar to that of 10,400 birds in the IUCN Red List of Threatened Species (i.e., 1,624 ± 48 webpages per organism; Correia et al., 2017), yet the variability in IS among invertebrates is substantially higher. Furthermore, our measures vary greatly from those obtained when entering vernacular names, i.e., 10,873 ± 4,372 for red-listed birds (Correia et al., 2017), 643-1,872 for

English popular names of Brazilian birds (Correia et al., 2016), 5,180-6.1 million for 180 popular Polish birds or 6,850-436 million for 52 common UK butterflies (Zmihorski et al., 2013). Such disparity is further accentuated by contrasting global internet salience of the monarch butterfly *D. plexippus* as scientific name (i.e., 70,100) versus popular name (i.e., 1.75 million) (see Fig. 2). Though our assessment is supported by Correia et al. (2017), who validated the use of scientific name frequency as a reliable indicator of public interest in nature, we also recognize that most invertebrates do not possess vernacular names. In the meantime, we do expect an important underrepresentation of IS for charismatic and well-known invertebrates (i.e., ladybirds, lacewings and hoverflies), such as the marmalade hoverly *E. balteatus* or the seven-spotted ladybird *C. septempunctata*.

Indeed, with IS below 643, a total of 194 (out of 339) biological control invertebrates receive comparable or lower global public interest than Brazilian hummingbirds, thus mirroring findings of Nemesio et al. (2013). Moreover, for 17.6% species, information can be obtained on less than 100 webpages worldwide. This is in stark contrast with pollinators such as *B. terrestris* or *A. mellifera* (IS 34,700 and 231,000, respectively) or disease-carrying mosquitos, i.e., *C. pipiens* or *A. aegypti* (IS 50,900 and 961,000, respectively). Hence, species with medical or human health importance receive vastly higher public visibility than those relevant to agriculture, or with important conservation value. A number of phenotypic and biogeographic traits, such as body size, aesthetic appeal (i.e., colorfulness) and commonness are likely determinants of species salience (Schuetz et al., 2015; Correia et al., 2016; Kim et al., 2014; Sitas et al., 2009, but see Zmihorski et al., 2013), and may explain the comparatively low IS for mites obtained in this study. Salience levels for certain groups, e.g. Coleoptera or Mantodea, are shaped by few colorful species of ladybeetles, species that excite curiosity (e.g., the ‘body-snatcher’ *Ampulex* *compressa* (Fabr.) IS 4,490 vs. SciS 380; Fig. 2) or the charismatic praying mantis, *Mantis religiosa*. Other organisms, e.g., the rove beetle *Dalotia coriaria* (Kraatz) (Fig. 2), feature on Wikipedia or are used regularly used as laboratory model organisms. Yet, for large-bodied parasitic hymenopterans, their complex and obscure lifestyle (e.g., as endo-parasitoids) can preclude broad public appreciation (e.g., Wyckhuys & O'Neil, 2007). Some of the above 'super-salient' species, i.e. those that attain comparatively high levels of cultural visibility (Correia et al., 2017), can readily be used as entry-points to frame broader issues of food safety, agricultural sustainability or wild-life friendly farming, and help bolster public understanding of biological control invertebrates (Ladle et al., 2016).

On the other hand, the world's biological control producers should be commended for adopting innovative marketing strategies to position some of the commercially-available agents. With product names such as *Dyna-mite, Macro-mite, ABS-System, Spidex* or *Ulti-mite*, biological control producers have indeed lifted the public profile of small-bodied Acari and secured a place for the minute *P. persimilis* among the world's five best featured invertebrate natural enemies. This tailored marketing approach may equally explain elevated IS for Nematoda, organisms that are broadly commercialized and require detailed application guidelines for in-field usage. Notwithstanding its relatively high search volume (i.e., 2,900 hits per month globally), the value of *P. persimilis* as a 'biological control emblem' (see Ladle et al., 2016) may be constrained by its small size and therefore may only find a soundboard among growers that are familiar with its use. Other larger-bodied organisms such as ladybeetles, praying mantids, pirate bugs (e.g., *O. insidiosus*) or *Oecophylla* spp. weaver ants likely feature far more prominently in (historical) cultural narratives, evoke wonder or curiosity, and thus could help muster popular support, funding or (possibly) farm-level adoption (Wyckhuys et al., 2018).

A careful (cross-cultural) analysis of organisms that evoke public interest, as enabled through culturomics, is particularly important given the overall negative public attitude towards invertebrates in general and specifically against insects. At a global level, insects –except for honeybees and a small set of aesthetically-appealing species- are regularly viewed with attitudes ranging from indifference, avoidance to outright fear (Kellert, 1993; Baldwin et al., 2008). In a survey of USA college students, overall knowledge of insects was limited to as little as 13 species, with organisms regularly dichotomized as either beautiful or bothersome (Shipley & Bixler, 2017), notwithstanding children's extensive knowledge about 'artificial' Pokemon creatures (Balmford et al., 2002). Similar attitudes exist in Switzerland and Japan (Breuer et al., 2015; Hosaka et al., 2017), while in Arizona (USA) only 6% of 1,117 households voiced pleasure upon encountering invertebrates outside their home. Human perceptions towards insects are molded by childhood encounters, species trait (i.e., aesthetic appeal) (Lemelin et al., 2016), and insects' cultural importance (Wyckhuys et al., 2018), thus imposing considerable bias towards colorful butterflies or (domesticated) pollinators. Though the growing public appreciation of honeybee pollinators is evidently to be applauded (Schönfelder & Bogner, 2017), biological control organisms provide equally valuable and economically-important services (Southwick & Southwick, 1992) and this attracts little public recognition.

Another way in which culturomics can help advance agro-ecology or insect biological control is by capturing (geographically-delineated) constituencies that are attuned to invertebrates (and their associated ESs), or where public perception towards e.g., biological control are less positive (Ladle et al., 2016). This is accentuated by a stark disparity in internet salience at the country-level (Fig. 1), partially due to restricted (commercial) availability of natural enemies in tropical Africa or South America (Schuetz et al., 2015). Yet, we note equally pronounced inter-country differences among western nations with a similar degree of agricultural development, literacy and adult education, or internet connectivity (e.g., France and Germany vs. USA). Given the multi-billion dollar benefits of biological control to USA agriculture and the key role natural enemies assume in numerous agro-production systems across North America (Losey & Vaughan, 2006; Naranjo et al., 2015), it is surprising to note their low visibility on national websites.

Particularly for knowledge-intensive technologies such as invertebrate biological control, availability of and access to (locally-relevant, digestible) information is essential (Wyckhuys et al., 2018). For multiple countries in the global south (e.g., Kenya, Thailand, Indonesia), the overall low IS of BC organisms could hamper diffusion of biological control, unless local extension programs are paper-based. Also, the low ‘culturalness; of biological control in these countries is likely magnified by an under-representation of key beneficiaries (i.e., farmers, farm workers) on the internet (Graham et al., 2015). More specifically, the mere visibility of 11/339 organisms in Tanzania might affect the establishment and steady growth of sustainable intensification programs, or the nation’s organic (cotton, coffee, cacao) farming sector and its 148,000 producers (Willer & Lernoud, 2016). Hence, our country-level mapping of visibility of biological control invertebrates has immediate implications for policy (Reganold & Wachter, 2016), development of tailored education and farmer extension programs, effective roll-out of incentive schemes (Naranjo et al., 2015) and the successful promotion of biological control as core component of sustainable food systems (Waterfield & Zilberman, 2012).

Conclusions

Agricultural development should not be a one-way process. Evidence now abounds of how intensified farming can undermine on-farm biodiversity and linked ESs, and how global food systems are founded on a fast-decaying basis (La Canne & Lundgren, 2018; Bianchi et al., 2006; Holland et al., 2014; Lundgren & Fausti, 2015; Hallmann et al., 2017; Tomasetto et al., 2017). As an integral part of ecologically-based farming practice, insect biological control -a millennia-old tactic and invaluable ES- can contribute to restoring and sustaining the world's farming systems. As access to information facilitates farm-level uptake and effective diffusion of biological control, our study pinpoints immediate opportunities for remediative education campaigns, awareness-raising efforts or (participatory) farmer extension programs. In addition to opening a new (digital) chapter of cultural entomology, our culturomics approach equally permits real-time tracking of the public appeal of insect-mediated ecosystem services, helps identify invertebrate organisms that could act as 'agro-ecology' emblems or flagships, and guides public policy. As the Intergovernmental Science-Policy Platform on Biodiversity & Ecosystem Services (IPBES) released its 2018 report (Scholes et al., 2018), emphasis was placed on incorporating (invertebrate) biodiversity in policy-making, recognizing peoples' capabilities to derive benefits from nature (Sangha et al., 2018), and realizing the central role of culture in examining links between people and nature (Diaz et al., 2018). Our work addresses all three of these themes, providing an unprecedented global perspective on the 'culturalness' of ecosystem-providing invertebrates, and helps advance their effective incorporation in decision-making at a global scale.

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Figure legends:

Figure 1. Global and country-specific relationships between *scientific salience* and *internet salience* for 339 different invertebrate biological control organisms. The number of web-pages obtained through Google Scholar and Google Custom Search API queries were used as proxy for scientific salience and internet salience, respectively. Internet salience is plotted on a log-scale and depicted either in absolute numbers (i.e., number of websites; A, B) or in relative numbers (i.e., proportion of websites for a particular country; C, D). Countries are organized on a continent-basis, combining Europe and North America (A, C) and the developing-world tropics (B, D). Statistics for the regression lines in each graph are described in the text.

Figure 2. Organism-specific relationship between *scientific salience* (i.e., number of GS records; log-transformed) and *relative internet visibility* for 327 biological control organisms belonging to eight key taxa. A relative internet visibility index is computed through *(IS-SciS)/SciS*. For ease of presentation, two organisms with high relative visibility were omitted from the graph, i.e., *Ampulex compressa* (Hymenoptera) at relative visibility = 10.81, and *Mantis religiosa* (Mantodea) at relative visibility = 19.54. The following key ecosystem service and disservice provider organisms are shown in the graph as black diamonds: 1. *Oecophylla smaragdina*; 2. *Danaus plexippus*; 3. *Bombus terestris*; 4. *Culex pipiens*; 5. *Aedes aegyptii*; 6. *Apis mellifera*; 7. *Macrocheles robustulus*; 8. *Leptomastix algirica*; 9. *Episyrphus balteatus*; 10. *Dalotia coriaria*. An interactive version of this graph can be found online at http://ec2-13-55-55-51.ap-southeast-2.compute.amazonaws.com:3838/Culturomics/.

Figure 3. Comparative *internet salience* (mean ± SE) of biological control organisms within six different taxa, as depicted on a country basis. Internet salience is computed for each individual organism based upon the number of web-pages obtained through Google Custom Search API queries, and then averaged per taxon. Accompanying statistics are outlined in the text.

Figure 4. Relationship between the *real-time public interest* and *internet salience* (log-transformed) of 339 biological control organisms, based upon the extent those feature on either global or country-level websites. Real-time public interest is reflected by the monthly search

volume for individual binomial scientific names (log-transformed), as computed through Keywords Everywhere either for a global search or for US- and UK-restricted queries. Regression statistics are represented in the text.

Table 1. Internet usage statistics for the select set of countries covered in this study. Specifics are included on the extent of internet coverage, degree of internet penetration and total country-code Top Level Domains (ccTLDs) for each individual country as per 2017.Internet penetration reflects % of the country's population with access to the internet, and was used to rank the individual countries.

Country	**Total internet users (in thousands)**	**Internet penetration rate (%)**	**Total no. of ccTLD* (millions)**
United Kingdom	62,354	94.8	12.1
Germany	73,436	89.7	16.3
France	55,413	85.6	3.1
Russia	110,003	76.4	6.2
United States	245,436	76.2	1.7
Brazil	123,927	59.7	3.9
Thailand	32,710	47.5	0.068
Indonesia	66,244	25.4	0.256
Kenya	12,600	26.0	0.058
Tanzania	7,224	13.0	0.015

***** Information about ccTLDs was obtained through Verisign (https://www.verisign.com) and IANA (Internet Assigned Numbers Authority; https://www.iana.org), by accessing individual country URLs

643 **Table 2.** Overview of the different metrics used in this study.

Metric	Description	Search engine	Spatial coverage	Formula
Scientific salience (*SciS*)	Number of scientific documents that feature a particular organism	Google Scholar	Global	-
Internet salience (*IS*)	Number of websites that feature a particular organism, indicative of its cultural visibility and/or interest	Google Custom Search	Global, country-specific	-
Relative internet visibility	Extent of public visibility or 'culturalness' relative to SciS of a particular organism	-	Global, country-specific	(*IS*-*SciS*)/*SciS*
Real-time public interest	Monthly search volume averaged over a 12-month time frame, reflective of online search behavior	Keywords Everywhere	Global, country-specific	-

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Table 3. Contrasts between organism-specific *scientific salience* and *internet salience* (mean ± SD) for a total of 327 globally-important biological control agents (representing major taxa), as organized by taxon. The number of web-pages obtained through Google Scholar and Google Custom Search API queries were used as proxy for scientific salience and internet salience, respectively. For each taxon, the association between the two individual measures of salience is also revealed by linear regression. Patterns for Mantodea, Chilopoda, Mollusca and Thysanoptera are not shown due to paucity of data.

Classification	**n**	**Scientific salience**	**Internet salience**	**Regression parameters**	**F statistic**	**R^2**
Acari	51	875.9 ± 1533.9a	1167.4 ± 2398.0a	y= -0.007 + 0.938x	$F_{1,49}$= 291.083, P< 0.001	0.856
Coleoptera	40	1544.4 ± 3013.9a	3089.2 ± 7120.9ab	y= 0.035 + 0.977x	$F_{1,37}$= 399.685, P< 0.001	0.915
Diptera	11	798.0 ± 1271.7a	2112.2 ± 3602.6ab	y= -0.024 + 1.171x	$F_{1,9}$= 55.224, P< 0.001	0.860
Hemiptera	24	1339.8 ± 1262.2ab	1951.8 ± 1741.2ab	y= 0.010 + 0.987x	$F_{1,22}$= 135.686, P<0.001	0.860
Hymenoptera	170	844.5 ± 1333.5a	1048.3 ± 1680.8a	y= 0.048 + 0.888x	$F_{1,168}$= 1742.721, P< 0.001	0.912
Nematoda	11	2701.2 ± 2731.1b	3550.7 ± 3814.4b	y= 0.054 + 0.897x	$F_{1,9}$= 112.510, P< 0.001	0.926
Neuroptera	20	876.5 ± 2225.1a	1258.7 ± 3392.6a	y= 0.021 + 0.947x	$F_{1,18}$= 209.291, P< 0.001	0.921
Statistics		$F_{6,319}$= 3.774, P= 0.001	$F_{6,320}$= 4.052, P= 0.001			

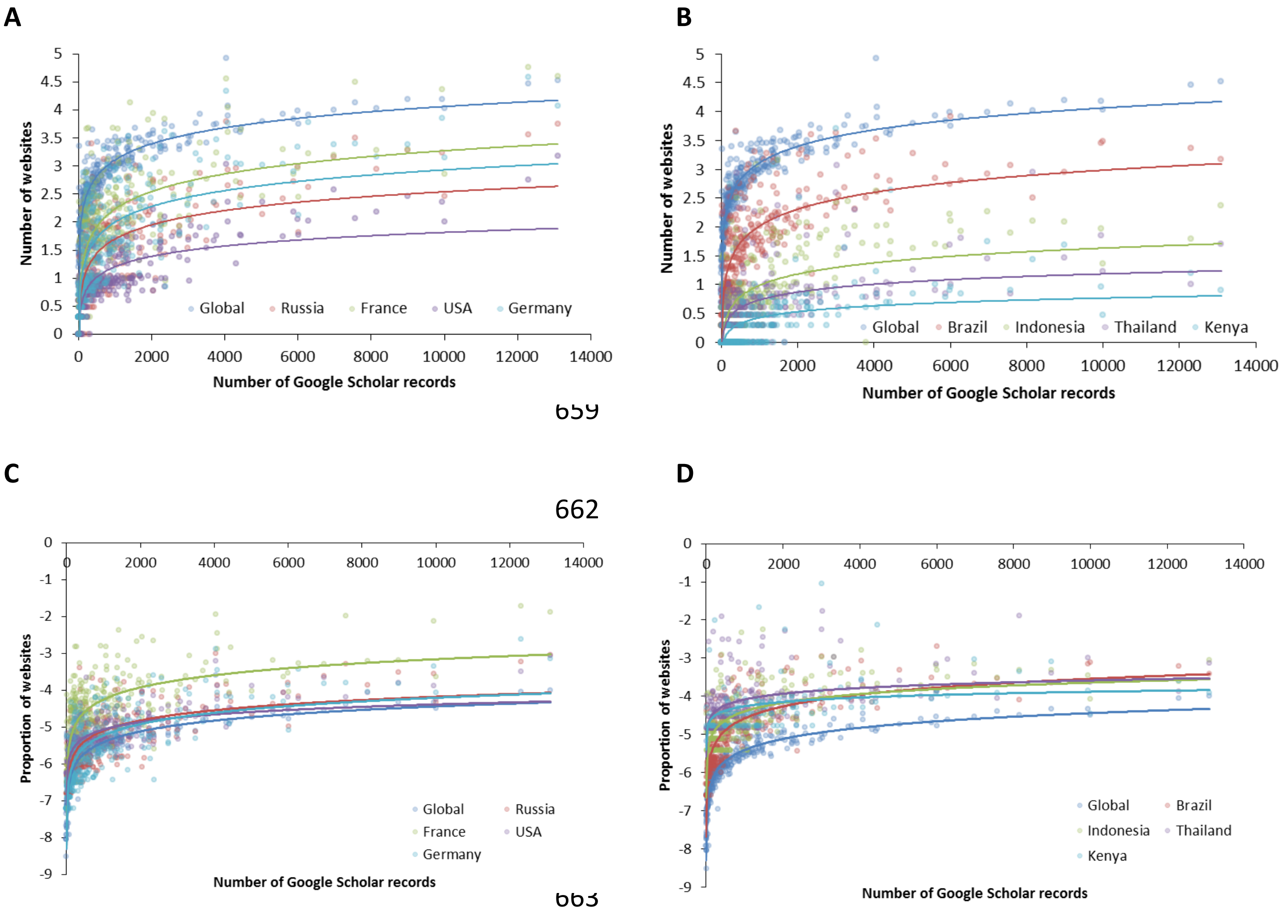

Figure 1.

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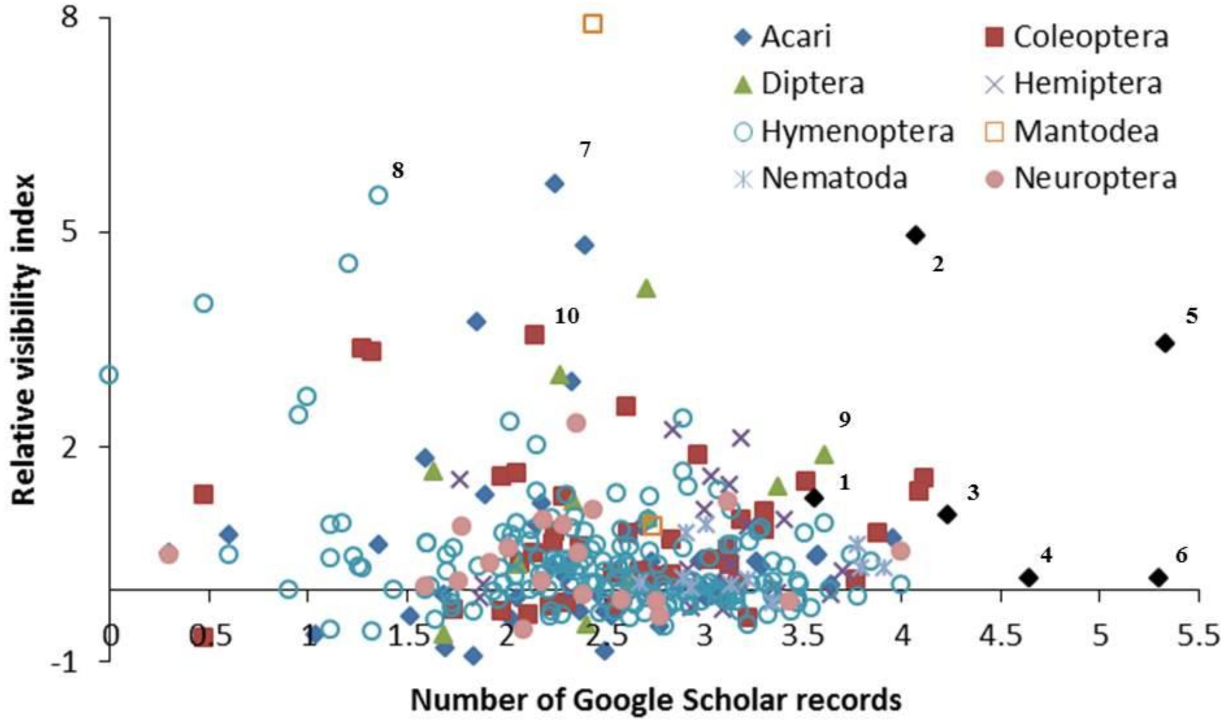

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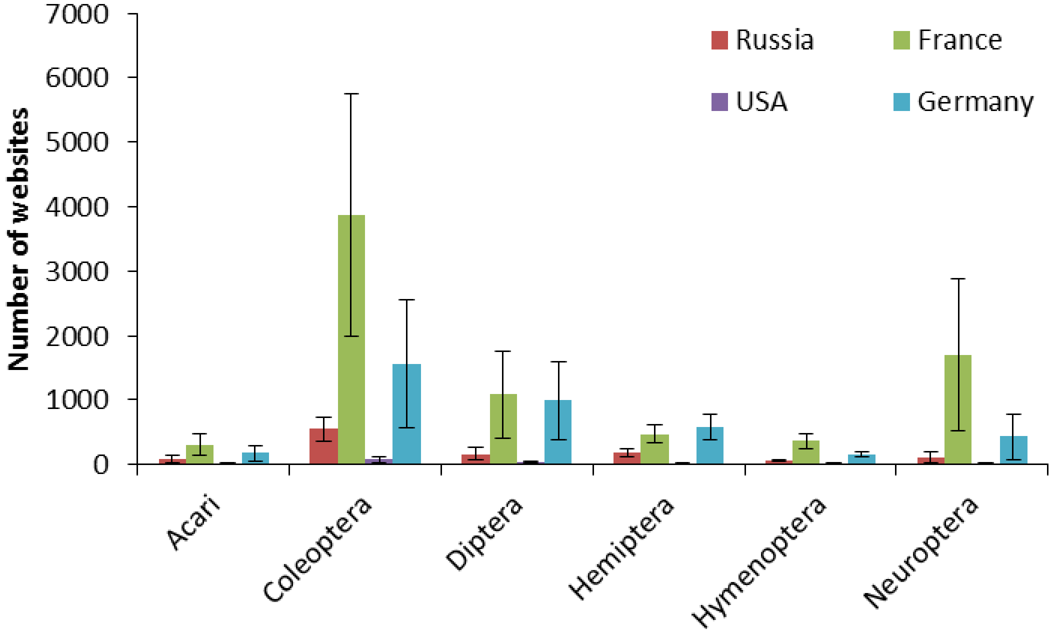
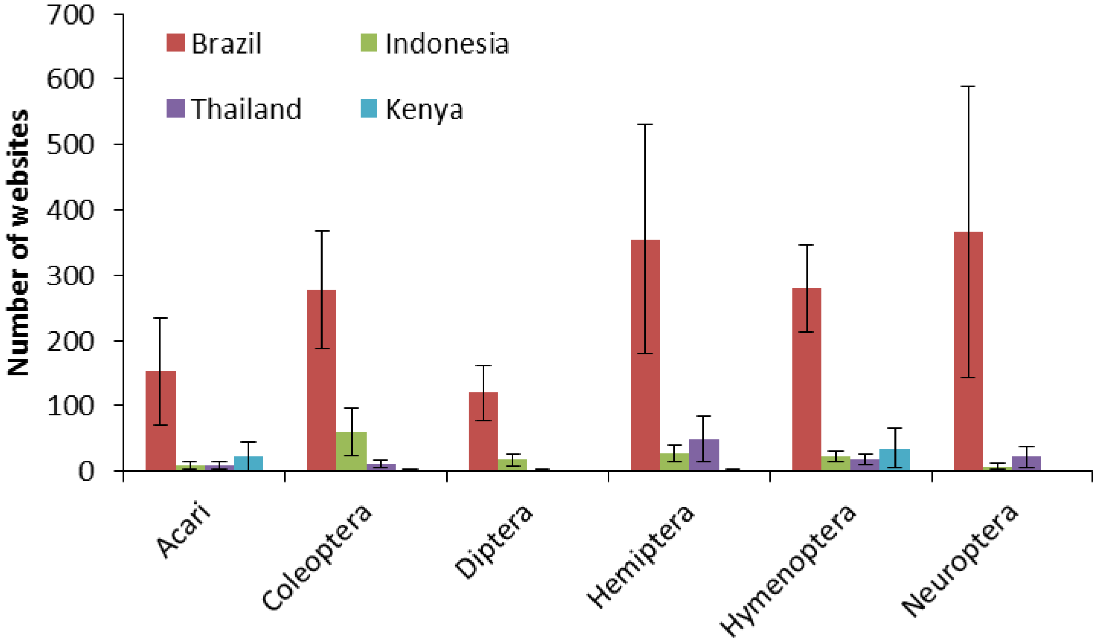
A



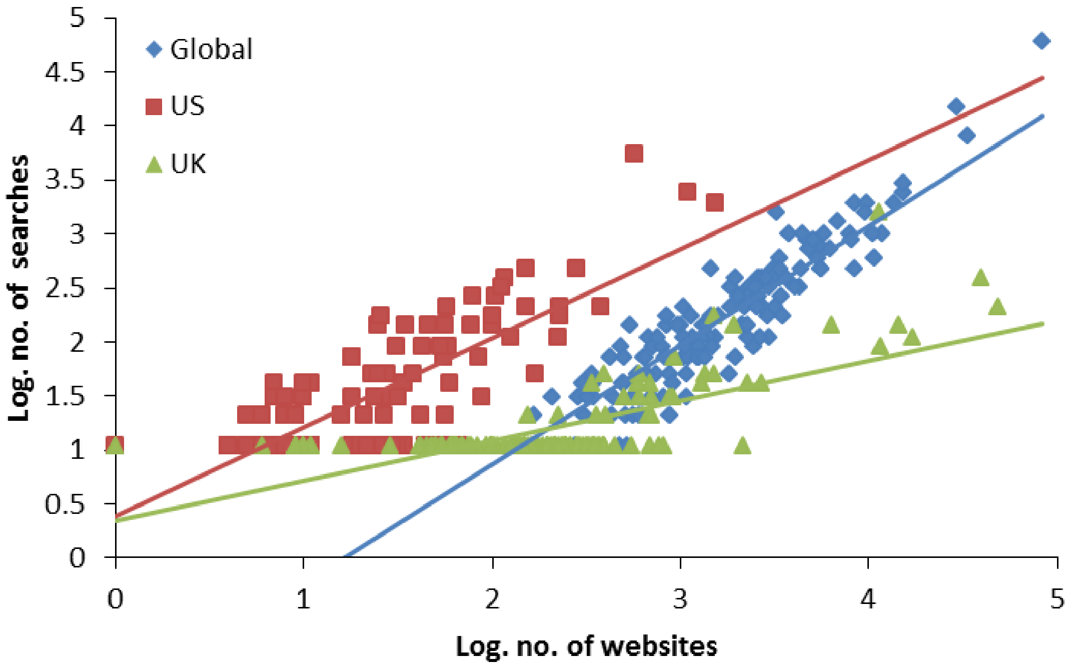
Number of websites
7000
6000
5000
4000
3000
2000
1000
0
Russia
France
USA
Germany
Acari
Coleoptera
Diptera
Hemiptera
Hymenoptera
Neuroptera

B



Number of websites
700
600
500
400
300
200
100
0
Brazil
Indonesia
Thailand
Kenya
Acari
Coleoptera
Diptera
Hemiptera
Hymenoptera
Neuroptera

Figure 3.



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686 **Figure 4.**
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