An analysis of historical trends in classical biological control of arthropods suggests need for a new centralized database in the USA

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The documentation of biological control agents targeting arthropods in the United States has historically been subject to less regulation relative to weed biological control releases. This study reviews publicly available databases to track environmental releases of biological control agents targeting arthropods in the United States. It then presents available data for the states with the most releases between 1962 and 2005: Hawaii, California and Florida. These data indicate a clear decline in rates of introduction since 1982 or 1994, depending on the source. Existing record-keeping systems offer incomplete or inconsistent data for evaluation because they were designed with limited goals, attempt to capture excessive detail and are thus impractical, or are insufficiently resourced. Existing databases cannot be used to answer meaningful questions regarding nontarget effects of introduced control agents. Current databases are inappropriately designed and insufficiently resourced to meet today's research and regulatory needs. We propose and describe a new database system for classical biological control of arthropods.

Keywords: classical biological control of arthropods, database, nontarget effects, risk/cost/benefit analysis, regulation

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Introduction

Quantification is essential to evaluating the success, obstacles and risks of any applied environmental science practice. The discrete tasks of classical biological control (foreign exploration, taxonomic identification, investigation of ecological relationships, host range testing, risk assessment, importation, release, monitoring, and biological and economic evaluation) lend themselves to being recorded in a systematic way (Gurr and Wratten 2000). Classical biological control of arthropods can be a practical alternative to chemical control practices (DeBach and Rosen 1991, Van Driesche and Hoddle 2000). While the steady decline in broad spectrum insecticide availability (Van Steenwyk and Zalom 2005, Warner 2007) may offer new opportunities for biological control programs in some commodities (Mills and Daane 2005), solid documentation and economic analysis of past efforts would bolster arguments for increased classical biological control funding.

The release of an exotic agent to the environment marks a key threshold with implications for assessing trends in classical biological control. Retrospective analysis of weed biological control agent introductions in the United States (Pemberton 2000)
is possible because a complete record exists of their releases (Julien and Griffiths 1998, Coombs et al. 2004). While far fewer weed agents have been released, they have been subject to much greater scrutiny relative to agents targeting arthropods (Coombs et al. 2004, Mason et al. 2005). Consequently, data for agents targeting weeds is more complete than data for agents targeting arthropods (Hunt et al. 2008). Retrospective studies of biological control agents targeting arthropods are constrained by this incomplete data (Follett et al. 2000, Louda et al. 2003, Stiling 2004), and these studies are further hindered by documentation practices that have not been systematic. Claims about the benefits of classical biological control of arthropods are thus difficult to substantiate.

Here we review databases and present an analysis of examples of biological control agents (BCAs) targeting arthropods in the United States (U.S.). We then propose a renewed effort to develop a centralized, comprehensive database to maintain historic and future data on biological control introductions targeting arthropods.

Current databases

Data collection for introductions of BCAs targeting arthropods occurs at four scales: international, national, regional (i.e., state), and quarantine. DeBach (1964), who was the first to publish a list of intentional introductions, listed 225 introductions of 107 arthropod BCAs targeting arthropods in 60 countries (or island regions) (1964, Table 12, p. 676 ff.). These data were drawn from a card file first assembled by Clausen, who later published it as a global review of all classical BCA introductions (Clausen 1978).

Greathead (1995) created BIOCAT, an electronic database of BCA introductions targeting arthropods by country, drawing from Clausen’s work plus numerous reviews of introductions by country. BIOCAT only contains records of the introduction of insect natural enemies targeting arthropods; it does not track pathogens or nematodes. Consisting of 13 fields, including information on targeted pests, natural enemies, crops where the pest is found, country and date of release, BCA, and result (Greathead and Greathead 1992), BIOCAT was annually updated by Greathead with data from scientific publications (Greathead, personal communication). BIOCAT has been used for retrospective analyses. For example, Lynch and Thomas (2000) and Lynch et al. (2001) used BIOCAT to analyze nontarget effects of introduced BCAs targeting arthropods with the 5,279 novel introductions identified in BIOCAT. Because BIOCAT depends upon published scientific articles, the database underestimates the total number of attempted introductions. In addition to observing that reporting of introductions is highly uneven between countries, Greathead and Greathead (1992) noted that many novel BCA introductions that fail to establish do not appear in scientific literature and, thus, are not found in BIOCAT.

In 1982, the U.S. Department of Agriculture - Agricultural Research Service (USDA-ARS) and its Biological Control Documentation Center (BCDC) created the Release Of Biological Organisms (ROBO) database in order to coordinate biological control research data collection, storage and sharing (Coulson 1992a). A USDA National Interdisciplinary Workshop on Biological Control (Battenfield 1983) endorsed this research tool:

> The second greatest overlapping need was to develop a computer-based data management system . . . [at] an information center available to all scientists in the crop.
protection disciplines. Such a center would increase interdisciplinary information exchange and participation of scientist in national programs, and it would probably increase the application of new technology in biological control research. Data stored in the system would include historical information, successful biological control programs, phenological information on all biological control agents, hosts, and targets, and simulation models of host-plant-pathogen systems (4).

ROBO was the U.S. Federal government’s effort to track BCA movement: importation to quarantine, movement from one quarantine to another or to a laboratory, and release to the environment. Data collection protocols treated all information with equal significance and thus did not distinguish between novel and subsequent releases of BCAs. By not differentiating novel from subsequent releases to the environment, the database cannot provide data for analyzing chronological trends in novel BCA releases (Biological Control Documentation Center 2005). ROBO depends upon quarantine officers entering data, and as of 2001, available data for 1981-1990 was posted on the world wide web (Coulson et al. 1988, Coulson 1992b, 1994, Biological Control Documentation Center 2005). In sum, the shortcomings of ROBO can be traced to the design of their data collection practices, the voluntary nature of reporting data, and the inadequate resources allocated to entering the data and maintaining a system.

Hawaii and Florida are the only states with published lists of novel BCAs released targeting arthropods. Funasaki et al. (1988), who were the first to compile a complete list of introduced BCAs for a single state (Hawaii), reported attempts to introduce 546 control agent species targeting arthropod pests for the period 1890-1985 (this data was updated and presented in Messing and Purcell 2001, Messing and Wright 2006). The Hawaii Department of Agriculture updated this list to cover 1890-2000, reporting 628 species of BCAs released targeting arthropods (Hawaii Department of Agriculture 2007). Frank and McCoy (1993) assembled a list of arthropods introduced to Florida. They subsequently published a list of 59 arthropod and one nematode BCA established 1899-2003, and 50 of these targeted arthropods (Frank and McCoy 2007).

Quarantine facilities serve as an obligatory checkpoint for the introduction of novel BCAs. Historically, USDA required permits for the introduction of exotic organisms, both from overseas into quarantine, screening out undesired organisms such as hyperparasites, and out of quarantine into laboratories for study and rearing. Historical data reporting requirements were chiefly for determining purity of insect cultures introduced into quarantine facilities. They were not meant to establish a record of the environmental releases of novel organisms nor to provide post-release monitoring data. Efforts to persuade researchers and quarantine officials to voluntarily contribute data have been hampered both by the absence of regulatory requirements to do so and by the perception that entry of data is an unnecessary clerical burden (Coulson 1992a).

Materials and Methods

We sought to determine trends in novel biological control agent releases by using publicly available lists of novel biological control agent species released targeting arthropods in the U.S. since 1962 (the year Silent Spring was published, Carson 1962). We focused on the states of Hawaii, California and Florida because they have been the most active states for the biological control of arthropods.
Because we were unable to extract novel environmental releases of BCAs targeting arthropods from ROBO, we could not use it. We were able to use the BIOCAT database (updated with published scientific literature to 2002), which includes a total 1,506 novel insect introductions targeting arthropods to the U.S. since 1890, and 363 between 1962 and 2002. These numbers exclude organisms not identified to species level, records of duplicate introductions, second attempts to introduce species, and undated records. We used the date of introduction by the first year attempted, even when subsequent efforts may have been decades later. If that date was ambiguous, we instead designated the year of journal article publication. We extracted entries for California, Hawaii and Florida, with all remaining states (identified specifically or not) grouped together. If a control agent was released to one of these three states and simultaneously in one of the other 47 states, we counted it only in the record of one of these three states.

We obtained the best publicly-available records on biological control agent releases targeting arthropods in these three states. The Hawaii Department of Agriculture has maintained an updated the list of BCAs released in Hawaii first assembled by Funasaki et al. (1988), and it makes a published version available (Hawaii Department of Agriculture 2007). We created a list of novel BCAs targeting arthropods by selecting organisms identified to the species level and entering them into a list by date of first introduction (1962-2006).

For Florida, we extracted a list of introduced species from Table 2 in Frank & McCoy (1993). We used the following criteria to select species for analysis: earliest listed date of release/importation as 1962 or later; identified to species level; indication of potential as biological control agent; and listed as having been released. We updated this list for the period 1993-present using Table 4 from Frank and McCoy (2007), which reports established BCAs up to 2005.

From the California Department of Food and Agriculture (CDFA) we obtained a record of Federal and state permits for arthropod introduction into California. This database has 1,615 Federal and 415 state permits for live organism introductions between 1968 and 2005. Before analysis, we removed all entries for commercially-reared natural enemies, lepidopteran species used for entertainment, laboratory research organisms, repeated (i.e., non-novel) introductions, and species native to California, in addition to weed control agents. Data for all three states were summed in Table 1.

Results and Discussion

Comparing BIOCAT and state specific records reveals that the majority of environmental releases of novel BCAs targeting arthropods in the U.S. have taken place in the three states for which we have specific data (Table 1). Hawaii has introduced the most BCAs targeting arthropods, followed by either Florida or California (depending on data source).

Between 1962-2005, fewer establishments or releases/permits were made during the latter half of this period with a general decline between 1994-2005. The decline for Hawaii was most pronounced. No novel BCAs were released in Hawaii 2000-2007 (Hawaii Department of Agriculture 2007). While this decline has been attributed to regulatory constraints (Messing and Purcell 2001), an alternative explanation may be the decline in agriculture’s demand for BCAs. Historically, the majority of BCA introductions targeted sugarcane and pineapple arthropod pests, but
these crops have declined significantly, e.g. the Hawaiian sugarcane crop in 2005 had only 25% of its 1986 value (Hawaii Department of Agriculture 2006). These industries funded or requested much of the biological control work targeting arthropods, so when their crops declined, funding for this work decreased concomitantly. Finally, the California permit database is of questionable value for tracking BCA releases; until 1975, no released BCA found in BIOCAT appears in the California database.

Table 1. Records of introduced biological control agents targeting arthropods in three states, 1962-2007

<table>
<thead>
<tr>
<th>State</th>
<th>BIOCAT records, 1962-2002</th>
<th>State specific records</th>
<th>State specific records indicate BCAs:</th>
<th>State specific records cover period:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawaii</td>
<td>124</td>
<td>137</td>
<td>Permitted and released</td>
<td>1962-2007</td>
</tr>
<tr>
<td>California</td>
<td>83</td>
<td>55</td>
<td>Permitted for release</td>
<td>1962-2005</td>
</tr>
<tr>
<td>Other 47 states</td>
<td>123</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>U.S. total</td>
<td>363</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Figure 1. BIOCAT database reported introductions into USA, 1962-2002, by year
Comparing these state-specific lists confirms the problems with the BIOCAT database. BIOCAT and data for Hawaii are quite similar because they both depended primarily on Funasaki et al. (1988). Since BIOCAT is based on published scientific literature, data in it is either incomplete or the date of introduction is significantly delayed. For example, the data spike in 1982 appears to be due to Coulson (1992b). BIOCAT did not, however, include a prior (Coulson et al. 1988) or subsequent report (Coulson 1994) compiling all the reported introductions from ROBO in 1981 or 1983 respectively. The 2005 edition of BIOCAT did not include Frank and McCoy (1993) and its list of species introduced to Florida.

Comparing these lists also indicates the limitations of the databases for Florida and California. The records for Florida suggest that many releases were attempted but that few species were actually recorded in the literature as successfully established (and thus entered into BIOCAT). California records suggest the reverse. The published literature reports 83 established species, but the permit database records 55. The state and Federal permit records begin in 1957 and 1970 respectively, but no novel introductions are recorded prior to 1976 (early entries are chiefly for commercial natural enemies).
New scientific and regulatory concerns suggest need for a new data collection system

The data collection and documentation of classical biological control targeting arthropods was created prior to concerns about nontarget impacts. These concerns have received considerable attention in the scientific community since the publication of Howarth (1991) (e.g., Simberloff and Stiling 1996, Louda et al. 1997, Strong and Pemberton 2000, Strong and Pemberton 2001). Howarth asserted that classical biological control introductions should be evaluated similarly to adventitious, invasive insects or weeds and evaluated for risk according to the same framework as transgenic organisms. Howarth and others (Coulson 1992b, Office of Technology Assessment 1993, 1995, Karieva 1996, Secord and Karieva 1996, Simberloff and Stiling 1996, Ewel et al. 1999, National Research Council 2002, Simberloff et al. 2005) have argued that the practice of biological control has much in common with the field of invasive species management. Concerns about nontarget effects of biological control have slowed the regulatory review of permit issuance and appear to be contributing to the general downward trend in introductions (Follett et al. 2000, Sheppard et al. 2003, Messing and Wright 2006).

Research and regulatory frameworks have generally shifted from targeting individual pests to the management of invasive species which disrupt ecosystems (Mack et al. 2000, National Research Council 2002, Hoddle 2004, Simberloff 2005, Lodge et al. 2006). Classical biological control has an important role to play in this, and this can be facilitated by making transparent its analytical framework for BCA introductions (Hoddle 2002). Delfosse (2005) proposed that biological control scientists need to take the lead in discussing the benefits of biological control, as well as the risks, and more stringent testing and monitoring protocols. A systematic approach to analyzing the risks and benefits of introduced species requires robust data sets and an analytical framework (Stohlgren and Schnase 2006). Invasive species management increasingly relies upon centralized databases containing data similar to those appropriate for tracking biological control introductions (Hoddle 2002). Delfosse (2005) proposed that biological control scientists need to take the lead in discussing the benefits of biological control, as well as the risks, and more stringent testing and monitoring protocols. A systematic approach to analyzing the risks and benefits of introduced species requires robust data sets and an analytical framework (Stohlgren and Schnase 2006). Invasive species management increasingly relies upon centralized databases containing data similar to those appropriate for tracking biological control introductions (Arzberger et al. 2004a, Graham et al. 2008). Analysis of how invasive species databases are constructed and used may provide lessons for designing a similar biological control database.

These developments have stimulated unprecedented scrutiny of the practice of classical biological control. The future of novel biological control releases targeting arthropods will likely be in partnership with non-biological control specialists, in conjunction with scientists and agencies dedicated to invasive species and ecosystem management and policy (Hoddle 2002, 2004). This suggests the importance of making historic and present data publicly available.

While emerging regulatory frameworks are one of the most pressing reasons for developing more thorough and publicly-available documentation of biological control releases, such documentation is also a prerequisite for conducting assessments of the economic benefits of biological control as a pest management strategy. Methodologically rigorous economic analyses of the costs and benefits of biological control are essential to help grower groups, research leaders, policy makers and the public better understand the value and potential benefits of investment in biological control. In his edited volume on biological control, Debach (1964) presented some of the first economic analysis of classical biological control, concluding that notably successful biological control projects resulted in a net benefit of $110M (real dollars, not adjusted for inflation) over the period 1923-1959. Debach’s analysis scaled up local estimates of the monetary savings from avoiding economic losses of crops on an
annual basis. Huffaker et al. (1976) carried forward the economic metrics developed by Debach and also found large returns on investment from classical biological control projects.

Gutierrez et al. (1999) identified key challenges to estimation of the benefits and costs of classical biological control: to gather appropriate economic data relevant to a project, to develop economic models comparing classical biological control with pesticides, and to incorporate risk perception and management into economic models. USDA researchers have published only one economic analysis of a classical biological control project targeting arthropods (Reichelderfer 1981). Some cost-benefit analyses have been conducted internationally (Voegele 1989, Van Den Berg et al. 2000, Bokonon-Ganta et al. 2002), but many of these suffer from methodological challenges, partly due to data limitations. In the United States, only a handful of cost-benefit studies of classical biological control have been conducted. Making more robust data available would spur more economic analysis of this type.

Proposal for a new database

Here we propose a new database to make biological control data available to a broader scientific audience. A data collection system should prioritize a complete record of novel environmental releases of BCAs targeting arthropods, and make this publicly available. In addition, it should make associated data sets derived from biological control research available to appropriate scientists and regulators, and be managed by a regulatory agency.

Current databases at the national and international scale were designed to serve the needs of researchers, not to inform environmental managers and policy makers. Because they were designed prior to nontarget concerns, the BIOCAT and ROBO databases cannot be used to prioritize data for the critical threshold of novel environmental release. Their data are derived from scientific publications and quarantine records respectively. BIOCAT is incomplete because novel BCA releases are only entered if published in a journal. ROBO’s design flaws are exemplified by its inability to distinguish novel from repeat BCA releases. Systematic analysis of classical biological control targeting arthropods is not possible using these databases because their design prevents the retrieval of a complete record of novel organism releases.

A contemporary documentation effort for classical biological control requires allotting resources to appropriate types of data, relative to their importance for environmental management and research. Taxonomic data of all introduced species, including all novel BCAs, is vital because regulatory agencies and environmental managers need a complete record of introduced species so as to identify them. Although most of the database would be publicly available on the Internet, some information could be deemed sensitive and made available only by request, thus ensuring that this data would not be used by non-scientists to tamper with biological control release projects. Because some researchers might object to the public sharing of data, determining exactly which data should be made available would require consultation with biological control scientists.

The data categories for a biological control database could be organized in the following way:

1. Pre-release data
   a. Systematics of natural enemy proposed for release
      i. Order, family, tribe, species
ii. Identifying expert
iii. Location of the voucher specimen identified by this expert

b. Biology of natural enemy
   i. Laboratory data: quarantine records and pre-release nontarget studies
   ii. Host records, performance and efficacy data, population dynamics
   iii. Predicted host range upon release

c. Documentation of material intended for release
   i. Collector(s) of source material
   ii. Geographic source of the material intended for release
   iii. Intended target, including systematics data
   iv. Host relationship
   v. Host records from literature and field observations

(2) Post-release data
   a. Field data
      i. Locations where species is released as control agent, including date, ecosystem and state where released (general region only)
      ii. Post-release monitoring data
      iii. Field nontarget data
   b. Analysis
      i. Economic data and evaluations
      ii. Pesticide reduction studies

(3) Supporting documentation
   a. Environmental Assessment
   b. Refereed publications
   c. Other publications

Two general sources of data are found at the Biological Control Documentation Center: permit records and historical “legacy” research data. Although USDA-APHIS typically sent copies of all biological control organism permits to the Biological Control Documentation Center, this record is not complete. Legacy data is information in the development of which an organization may have invested significant resources and which has retained its importance, but which has been created or stored by the use of software or hardware that is outmoded or obsolete. Legacy data are important because they identify historical biocontrol agents that have been released but have the potential to dramatically expand their population and disrupt native species and ecosystems (National Research Council 2002). Meta-analysis of larger scale patterns depends upon accessing this type of data. Recent trends in meta-analysis demonstrate the importance of making publicly funded research data openly available to the maximum extent possible (Arzberger et al. 2004b).

USDA –APHIS would be a logical agency to develop and maintain the biological control database system, although it would need to work closely with practitioners to ensure such a system functioned as intended, and no inappropriate data is made public. It has statutory authority for protecting plant resources and the environment and now has primary responsibility for regulating terrestrial invasive species (National Research Council 2002). It should thus collect and assemble legacy data and require the submission of future data. USDA-APHIS - Plant Protection and Quarantine has responsibility for issuing permits for novel organism releases (Mason
et al. 2005). It now requires a form of Environmental Assessment for all novel releases of BCAs targeting arthropods (making this analogous with regulation with BCAs targeting weeds). USDA-APHIS-PPQ has recently begun an electronic permitting system that will allow all future data be made available, and thus future data could be fed into a database system (Hunt et al. 2008). If this system is successful, data for weed biological control could also be made available through it.

Database development proceeds logically into three stages. First, a complete list of novel BCAs targeting arthropods released and available identification data (item 1, above) should be entered into the database. When available, data for categories 2a and 3 should be entered. Economic and pesticide reduction analysis (2b) would be added as data becomes available.

There is typically little incentive to conduct economic analyses of biological control, but a more efficient data collection might facilitate collection of economic data, in collaboration with university researchers. This database should be designed with fields so that researchers can enter economic data, such as crop yield responses to pest damage, efficacy at different levels of infestation, longitudinal effects on infestation, and all relevant costs for biological, cultural, and chemical control. These data could facilitate more economic analysis of invasive species management and the comparison of biological control with other strategies.

**Conclusion**

This study analyzed data of environmental release records of BCAs targeting arthropods in three states. BIOCAT, ROBO, and the other databases were developed before nontarget impacts of BCAs targeting arthropods were of concern. While the comparison of two databases suggests that the record for Hawaii is fairly complete, records for California and Florida are not. BIOCAT indicates a clear decline since 1982, and the three states’ databases indicate a general decline in releases 1994-2005. The decline of release rates in Hawaii has been particularly pronounced.

Given the criticism, controversies, and regulatory difficulties surrounding the introduction of novel BCAs, the most striking findings from this study are the incompleteness of data, and the inadequacy of data collection protocols for releases of BCAs targeting arthropods. Current data collection practices were appropriate for an earlier period of biological control research and regulation, but no longer suffice. Research and regulatory frameworks have shifted from projects targeting individual pests to landscape and ecosystem management, so data management must undergo a similar evolution.

This proposal for a new documentation system would assemble and share data so that biological control of arthropods could be better used as an invasive species management strategy. A logical agency to record and share biological control data is USDA – APHIS – Plant Protection and Quarantine, which has statutory authority for protecting plant resources and the environment. Classical biological control has the potential to manage invasive arthropods, but without a systematic approach to gathering and sharing data, its benefits will not be adequately documented. The failure to adequately document benefits may have indirectly contributed the decline in release rates. Our proposed initiative will advance the science of biological control by making information about its benefits available to environmental scientists and policy makers.
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