1.1 Accidental Introductions of Natural Enemies: Causes and Implications

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Accidental introductions of natural enemies, including parasitoid and predatory groups, may exceed species introduced intentionally. Several factors favor this: a general surge in international trade; lack of surveillance for species that are not associated with live plants or animals; inability to intercept tiny organisms such as parasitoids; huge invasive host populations in source and/or receiving areas that allow rapid establishment; and lack of aggressive screening for pests already established. Recent frequent and surprisingly rapid accidental natural enemy introductions call into question the regulatory emphasis on a rigorous and protracted process for classical biological control (CBC) introductions, when adventives have a high probability to displace or disrupt this planned process. We provide an overview with three brief case studies.

The volume of global international trade is staggering, and it continues to increase. International shipping moves 127 million containers (TEUs, each ~40m³ in volume and weighing ~14 tonnes) per year between countries, the majority between continents, for a total of ~5 billion m³ of freight (2014 totals; World Shipping Council, 2017). About 4x this amount moves domestically in coastal shipping. Additionally, 3.2 billion passenger trips take place by air, and air freight amounts to ~185 million tonnes (about 1/50th of the weight shipped by boat, but delivered in <1 day) (2014 totals; World Bank, 2017). A single adult parasitoid weighs about 1 mg (Harvey *et al.*, 2006), or approximately 70 parts per trillion of a single shipping container – less than a needle in a haystack – and 350,000 such haystacks arrive from foreign ports worldwide *per day*!

Given this massive exchange of merchandise, invading natural enemies are of low to vanishing priority for national authorities inspecting imports for harmful organisms and other threats. Primary concerns are plant and animal pests and pathogens that will do the most serious and immediate damage, not to mention a host of other non-biological concerns such as terrorism, hazardous substances, and material that is illegal, smuggled, and/or counterfeit. In the US Department of Agriculture, the very name APHIS PPQ (Animal and Plant Health Inspection Service, Plant Protection and Quarantine) reflects these priorities, and, aside from known plant and animal pests and pathogens, and their associated carriers, very little else attracts the attention of border patrol inspectors.

Reece Sailer, in a prescient perspective, estimated the number of “beneficial immigrant species” to the US, determining that nearly half (134 of 287=47%) had been accidentally introduced (numbers from his Figure 6, not his text). “As an entomologist specialized in

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introduction of beneficial insects, I find it disconcerting...” (Sailer, 1978). He cited as “valuable” many of the accidentally-introduced species such as San Jose scale parasitoid, *Prospaltella perniciosi* Tower (Hymenoptera: Aphelinidae), and the alfalfa leafcutter bee, *Megachile rotundata* (F.) (Hymenoptera: Megachilidae). A few years later, Sailer (1983) provided a breakdown of the 232 alien “beneficial Hymenoptera,” of which 82 (35%) had arrived accidentally; of the remaining 150, 10 had entered the US from Canada after being introduced intentionally there, and the remainder were intentionally introduced to the US by USDA and University of California scientists.

Roy *et al*. (2011) provide a very thorough recent analysis for alien arthropod predators and parasitoids, based on the DAISIE database for European alien species. Of the estimated 1590 species of arthropods introduced to Europe, 513 (32%) are predatory or parasitic. Of these, 66% were introduced unintentionally. This survey includes a number of groups that would never be considered for CBC introductions, e.g., ticks, fleas, spiders, and social Hymenoptera. Of the parasitoid Hymenoptera, 60 (28%) of the 212 recorded alien species were accidental (unintentional) introductions (Roy *et al.*, 2011-Table 1).

From these two assessements, widely separated in space and time, at least one-third of alien natural enemy species appear to have been introduced accidentally. This is probably an underestimate, given the paucity of knowledge of these faunal groups. Furthermore, the proportion of accidentally introduced species has increased recently, as the number of intentional introductions has decreased, due to more stringent criteria for CBC introductions (Roy *et al.*, 2011-Fig. 3; Hajek *et al.*, 2016a).

Several major invasive pests have been associated with accidental introductions of their natural enemies, with varying outcomes, some still unclear. Below is a brief overview of three examples: gypsy moth, brown marmorated stink bug, and kudzu bug.

Since its discovery in northern Georgia (USA) in 2009, kudzu bug, *Megacopta cribraria* (F.) (Hemiptera: Plataspidae), has been considered a very serious threat to the US soybean, *Glycine max* (L.) Merrill (Fabaceae) crop. Overwintering on kudzu, *Pueraria montana* var. *lobata* (Willdenow) Maesen & S.M. Almeida ex Sanjappa & Predeep (Fabaceae), an invasive woody vine native to Asia, it colonized soy crops and reached very high densities (Gardner *et al.*, 2013) which were very damaging to yields, unless pesticides were applied. In 2013, the scelionid *Paratelenomus saccharalis* (Dodd) (Hymenoptera: Scelionidae) was detected in northern Georgia, and the next year, in 4 additional states (Gardner and Olson, 2016). The origin is unknown and is presumed accidental (Gardner *et al.*, 2013). A CBC assessment for *P. saccharalis* was underway in quarantine at the time of appearance of this adventive population, which was shown to be distinct from the quarantine rearings (W. Jones, personal communication). Meanwhile, as early as 2010 (Ruberson *et al.*, 2013), the cosmopolitan generalist fungal entomopathogen, *Beauveria bassiana* (Balsamo-Crivelli) Vuillemin (Clavicipitaceae) was noted as attacking kudzu bug, and in 2015, many locations had outbreaks of this pathogen. The pathogen, possibly complemented by *P. saccharalis*, is thought to have caused greatly reduced regional kudzu bug populations (Gardner and Olson, 2016; Blount *et al.*, 2017). It remains to be seen if kudzu bug is vanquished or will rise again in North America.

A second example of a scelionid egg parasitoid accidental introduction is covered in detail by Hoelmer *et al.* (this volume, 1.3). Nearly twenty years after the introduction and spread of the brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) in North America, the Asian scelionid *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) oviposited in three sentinel BMSB egg masses in Maryland, USA (Talamas *et al.,* 2015), and has since been detected in several other eastern and western USA. Bon *et al.* (this volume, 2.6) document at least 3 separate lineages, corresponding to separate accidental introductions of *T. japonicus* into North America. None of these match with cultures held in quarantine for study under a CBC program. Native parasitism has been sporadic and mostly low (Hoelmer *et al*, this volume). However, population declines have been noted in BMSB rearings and in the field, and some of these may be due to a newly-discovered microsporidian, native to North America and pre-dating the introduction of BMSB (Hajek *et al.*, in review). Once again, the plot thickens!

Classical biological control using pathogens (including nematodes) has been infrequently practiced, relative to arthropod CBC introductions. Worldwide, only 70 pathogen species have been introduced for CBC, with a correspondingly low number of 7 species accidentally introduced (Hajek *et al.*, 2016b). However, two of these accidental introductions have played a large role in biological control of invasive gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Erebidae) populations in northeastern USA. The first was the introduction of Lymantria dispar multiple nucleopolyhedrovirus (LdMNPV), thought to have been introduced in the early 20th century with parasitoids or plant material, as part of an extended and extensive arthropod CBC effort. During most of the 20th century, this virus, which was later mass-produced and formulated for application by the USDA Forest Service and APHIS, caused epizootics in high-density defoliating gypsy moth populations, resulting in rapid population crashes, and spreading naturally with the host population (Hajek and Tobin, 2011).

The source of the second introduction was initially surrounded by some uncertainty (Hajek *et al.*, 1995). The source of this pathogen was addressed using molecular techniques as well as historical data (Nielsen *et al.*, 2005; Weseloh, 1998) that showed with near certainty that this was an accidental introduction. In 1989, *Entomophaga maimaiga* Humber, Shimazu & Soper (Entomophthorales: Entomophthoraceae) was found in 7 states of the northeastern US. Within 5 years, this fungus had spread to all contiguous states infested by gypsy moth, and host populations in many areas have remained low for most years since. Although released intentionally in 1910-1911, there was no evidence that it established then, and there were many favorable chances to observe the effects of the pathogen in the US between 1911 and 1989 (Hajek *et al.*, 1995; Weseloh, 1998). Another effort resulted in releases in 1985 and 1986, but these were shown to be a different strain and were geographically distant from the 1989 epizootics when *E. maimaiga* was first found in the US (Nielsen *et al.*, 2005).

With the increased focus on guarding against nontarget effects of CBC comes the cost of delay and reduction in number of projects carried out (Hajek *et al.*, 2016a). While this may in some cases prevent negative ecological consequences, criticisms of long-past classical biological control mistakes are today largely misplaced. Calls for more regulation and involvement of all stakeholders (e.g., Blossy, 2016) set up the perfect as the enemy of the good. Practical CBC should strike a balance to solve problems as much as it should seek to avoid creating new problems. With increased delay, perhaps CBC agents and plans may be optimized over more time, and native natural enemies may adapt or intersect with the targeted invasive pest in the interim. More certain though, is the prospect of prolonged and even irreversible ecological and economic disruption from pest damage, pesticide applications, and lost ecological services. Along with delay comes the prospect that accidental introductions of potentially suboptimal natural enemies occur, removing the chance to address pest invasions in a timely manner through best scientific practices.

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