**An update on Australia’s use of remote sensing to predict risk maritime pathways for gypsy moths (*Lymantria* spp., Lepidoptera: Erebidae) –operational results for 2011-2013.**

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**Abstract**

Australia’s use of remote sensing or geospatial intelligence to predict risk seaports for Asian gyspy moths has lead to an increase in the number of gypsy moth egg masses intercepted on maritime vessels. Here, we present interception data from 2011 to 2013 and discuss potential future development of our approach to gypsy moth surveillance. The risk posed by different vessel types is also discussed, along with the utility of new and future LED light sources as a potential way to avoid AGM contamination of maritime vessels and seaport infrastructure in the future.

**Introduction**

Asian gypsy moths (*Lymantria* spp., Lepidoptera: Erebidae; AGM) are among the most serious quarantine pests for Australia. *Lymantria* spp. are known to be forest defoliators, causing severe damage to forestry production. For example, damage caused by the introduced *Lymantria dispar dispar* in eastern North America has been estimated to reach US$400 million per plantation per cropping cycle (Maryland Cooperative Extension 2007), while the ongoing suppression program for this population is estimated to provide an investment return of at least 3:1 (Sills 2008). Literature records for one taxon (*Lymantria dispar* sensu lato) indicate it has been able to damage over 1600 species of plant in either wild or laboratory situations. Known host plants of several *Lymantria* species form the mainstay of Australian forest production, including species of *Eucalyptus* and *Pinus*. The introduction of forest defoliating *Lymantria* taxa to Australia is likely to have irreparable consequences for the Australian forest products industry.

From an Australian quarantine perspective, the majority of interceptions are made from maritime vessels that have visited seaports where AGM are endemic. The vessels become contaminated when female moths, attracted to light sources associated with seaport infrastructure, land on the vessel and lay eggs after settling (Koshio 1996). Analysis of the light spectra that attract AGM females (Wallner *et al.* 1995) has demonstrated that attractive spectra are emitted by virtually all commercially available light bulbs (General Electric 2009), making them at least partially attractive. As contamination is relative non-selective in that any item located at an AGM-endemic seaport can become contaminated, border management of AGM has relied on blanket approaches, such as inspecting all vessels that have visited seaports within a defined geographic area deemed to be of high risk for AGM. However, the sheer volume of maritime traffic from areas where AGM are endemic makes it difficult from a resource management perspective to inspect all vessels in an effective manner. Other attempts to identify specific risk pathways are probably limited because they rely on different attractants, such as male pheromones (Munson 2008), to those responsible for pathway contamination (lights).

Recent studies of AGM dispersal into urban areas in Japan (Liebhold *et al.* 2008) demonstrate that the density of female moths ovipositing decreases with distance from habitat stands. Specifically, Liebhold *et al.* (2008) found no evidence of egg masses associated with light sources more than 1500 metres from areas of suitable host plants. Although AGM taxa are polyphagous, their preferred host plants are a circumscribed group of genera (eg. *Quercus, Larix* and *Pinus* spp.) (Pogue and Schaefer 2007) that tend to dominate and define forest types in temperate Eurasia. This in turn makes it possible to identify AGM-host dominated forests by their spectral reflectance patterns, which have been measured by a number of large-scale remote sensing studies and made available as proprietary commercial products (Globcover 2008). By mapping the distribution of forest types likely to be comprised of AGM hosts, it was possible to objectively identify seaports in Asia that were within known dispersal range of AGM, and were therefore likely to pose a risk of AGM contamination (Nielsen, 2011).

The method of Nielsen (2011) can be described as follows. The biosecurity risk posed by exotic *Lymantria* taxa travelling via maritime vessels was identified using standard pest categorisation methods (FAO 2004). These species (Appendix A) were *Lymantria dispar asiatica, L. dispar japonica, L. umbrosa, L. mathura, L. monacha* and *L. xylina*. However, *Lymantria xylina* was subsequently removed from consideration due to a lack of interception records from maritime vessels anywhere in the world. Any seaport within the distribution of the AGM pest taxa was considered for geospatial analysis. Seaports supporting existing (known) maritime pathways to Australia were identified Departmental vessel inspection records and industry resources (World Port Source 2009; Lloyd's Marine Intelligence Unit 2005), or by a dedicated search for seaport facilities using satellite and aerial imagery (Google 2010). The latitude and longitude of each port considered for analysis were collected from industry data or manually identified (Google 2010, World Port Source 2009). A set of spectral data for world forest cover, which also identified forest types (Globcover 2008), was then used to produce forest cover maps for an area of 30 square kilometres surrounding the seaport’s geo-coordinates (Appendix B). As Liebhold *et al.* (2008) identified that *Lymantria dispar japonica* could penetrate human habitation for as far as 1500 metres, Nielsen (2011) used a maximum penetration distance for AGM of 2000 metres to allow for less brightly lit urban environments than Japan. The map for each seaport was then overlaid on Google Earth (2010) to further verify the seaport’s risk through a 3-dimensional examination of site topography. The location of vessel berthing sites were also manually added using a marker with a 2000 metre risk radius to ensure accuracy. Any seaport with berthing sites located within 2000 metres of AGM risk vegetation were then regarded to be a potential high risk AGM seaport (Appendix C).

To verify the accuracy of the geospatial analysis conducted by Nielsen (2011), the Department of Agriculture conducted a series of trials based on the inspection of maritime vessels from the identified risk seaports in Asia. Here, we present the interception data collected to date and discuss the utility of geospatial intelligence as a risk assessment tool. We also suggest potential uses for data obtained through targeted surveillance, such as developing a forecast model for when individual seaports will present an AGM contamination hazard, and their potential savings to quarantine operations and industries dependent on maritime sea traffic for commerce.

**Materials and Method**

***Surveillance and Identification***

The Seaports program in the Department of Agriculture conducted a pilot surveillance study for *Lymantria* taxa on maritime vessels. The surveillance methodology was designed using ISPM guidelines as its basis (FAO 1997), meeting the definition of specific surveillance. The pilot study was conducted from 1 July 2011 to October 2013. The trial modified the surveillance criteria by restricting inspections to vessels arriving at the four Australian first ports expecting to receive the highest number of vessels eligible for surveillance (Gladstone and Brisbane, Queensland; Newcastle, New South Wales and Port Headland, Western Australia). Inspections were also conducted at the discretion of individual seaports based on staffing and resource availability (ie. not all vessels departing from identified risk ports were inspected).

Egg masses recovered during the trial were preserved immediately in 70% ethanol, allowing both morphological and molecular methods to be used in their identification. Morphological identification techniques were used in the first instance to establish the egg masses belonged to *Lymantria.* Molecular methodology for identification of egg masses identified as *Lymantria* followed (deWaard *et al.* 2010). Egg masses not identified as *Lymantria* taxa were identified from DNA sequences using the BLAST algorithm and reference sequences from GenBank .

**Results**

***Surveillance and Identification***

The surveillance trial inspected a total of 478 vessels departing from 11 potential risk ports between 1 June 2011 through to October 2013 (Table 1). 2012 was a peak year for AGM, with numerous interceptions of egg masses made both in Australia and elsewhere (D. Holden & N. Kummen, pers. comms.). The interceptions show that an outbreak of AGM occurred in Asia during 2012, with interceptions higher before the outbreak in 2011 than after the outbreak during 2013. This pattern reflects the cyclic nature of AGM outbreaks (Pogue and Schaefer 2007). Similarly, 2011 saw the interception of fewer egg masses than during the outbreak year, but more than in 2013. It may now be some years before another peak season occurs. The use of a vessel questionnaire on AGM contamination, faxed to vessels prior to arrival in Australia while they are underway, may also have reduced interceptions in 2013, as the information in the questionnaire was reported to have prompted many vessel masters to task their crew with the detection and removal of egg masses.

**Discussion**

Since employing remote sensing techniques to shape border surveillance for AGM, Australia has greatly increased the number of AGM interceptions. Since 2000, Australia had intercepted a total of six vessels (all from the Russian Federation, which was subject to mandatory inspection arrangements). However, since 2011, Australia intercepted 478 egg masses from 30 vessels, mostly bulk carriers and a smaller number of cargo vessels. This represents a five-fold increase in AGM interceptions from pathways from which AGM egg masses had never, historically, been collected by Australian quarantine operations.

**Table 1 *Lymantria* egg mass interceptions from the geospatial surveillance program**

|  |  |  |  |
| --- | --- | --- | --- |
| **Country** | **Source seaport** | **Vessel interceptions & breakdown** | **AGM egg masses intercepted** |
| **2011** |
| Japan | Fukuyama | 4 x Bulk Carrier & 1 Cargo | 19 |
| Mizushima | 2 x Bulk carrier | 40+ |
| Tachibana | 1 x Bulk carrier | 2 |
| China | Lionyunggong | 1 x Bulk carrier | 6 |
| **2011 Totals** | **9 vessels** | **67 egg masses** |
| **2012** |
| China | Nanjing | 1 x Bulk Carrier | 26 |
| Japan | Fukuyama | 4 x Bulk Carriers | 186 |
| Matsushima | 1 x Bulk Carrier | 55 |
| Mizushima | 7 x Bulk Carriers | 110 |
| Tachibana | 1 x Bulk Carrier | 5 |
| South Korea | Dangjin | 2 x Bulk Carriers | 16 |
| Gwangyang | 1 x Cargo | 16 |
| **2012 Totals** | **17 vessels** | **414 egg masses** |
| **2013** |
| Japan | Fukuyama, Japan | 1 x Bulk Carrier | 4 |
| Nagoya, Japan | 2 x Bulk carriers | 3 |
| Nanano, Japan | 1 x Bulk Carrier | 6 |
| Tsuruga, Japan | 1 x Bulk Carrier | 19 |
| South Korea | Taean, South Korea | 1 x Bulk Carrier | 1 |
| **2013 totals** | **6 vessels** | **33 egg masses** |
| **Total AGM vessels intercepted (2011-2013)** | **30** |
| **Total AGM egg masses intercepted (2011-2013)** | **514** |

As noted by Nielsen (2011), vessel type is expected to play a significant role in the likelihood that vessels will be contaminated by AGM egg masses. The major factors likely to influence the risk of contamination for different vessel types are how long vessels remain in port, the type and amount of lighting required for loading/unloading operations conducted in the AGM risk port, and the amount and type of lighting on the vessel itself. Light sources are known to affect attraction of AGM in the Russian Far East (Wallner *et al.* 1995), with light sources with peaks in the UV-range being more attractive. It is interesting to note that bulk carriers represent the majority of vessels from which egg masses have been intercepted in Australia. Only two of the 30 vessels found to be contaminated by AGM eggs were not bulk carriers. This result is expected, as bulk carriers tend to arrive in Australia empty and return to Asian ports loaded with coal. Unloading coal is a time-consuming process that often requires bulk carrier vessels to remain in a given seaport for several nights, making them more vulnerable to AGM contamination. In some instances, it was noted the Japanese government authorities had inspected and cleared vessels of AGM contamination, only for contamination to occur on the following night. It is also expected that bulk carriers will be more likely to visit remote seaports that are closer to forests than other vessel types (eg. roll-on roll-off vehicle carriers and cargo freighters), as bulk cargo requires mass-movement infrastructure (eg. dedicated freight railway lines) that are impractical in densely populated areas. RORO and cargo freighters, in contrast, tend to utilise seaports in built up areas, as existing infrastructure (roads) is largely suitable for trade.

Light source attractiveness has already been identified as a major issue affecting the risk of AGM contamination (Wallner *et al.* 1995). As already noted, the most attractive light sources had wavelengths peaking in the UV spectrum (<480 nm). Although unquantified, observations of the attractiveness of modern LED light sources emitting white light suggest they may prove suitable as AGM-neutral light sources. In Australia, white LED chip lights fail to attract Lepidoptera, while known attractive light sources (eg. phosphor coated mercury vapour lamps) used in the same situation attracted large numbers of moths and induced them to settle (J. Nielsen, pers. obs.). LED light sources are unique in that it is possible to design them to emit specific spectra by modifying the metallic composition of chip semiconductors. In contrast, it is impractical to modify the spectral output of incandescent or fluorescent light sources. Modified bulbs of this type tend to be reserved for specialist purposes. Most light sources do emit AGM attractive spectra (General Electric 2009), and specialist measures (ie. UV filters) were required to effectively reduce their attractiveness (Wallner *et al.* 1995). Modern white LED technology utilises an LED producing blue light (ca. 450 nm), which is modified by a phosphor to produce emissions through the 500-700 nm range (Tanabe *et al.* 2005). Light produced in this way does not produce spectra attractive to AGM. In contrast, UV-emitting LEDs use semiconductors containing aluminium to produce shorter wavelengths, with the ratio of aluminium to other semiconductor components determining the wavelength (Cooke 2010). Ongoing advances with LED lights may help to reduce the AGM risk to maritime vessels in even high risk seaports. In contrast, the use of decoy lights to trap AGM before they reach vessels in ports may prove impractical. Studies on moth attraction to UV light sources indicate that most moths respond to light within 5 metres of their location in the environment, with response then decreasing substantially with distance (Truxa and Fiedler 2012). In attempting to ensure adequate coverage, decoy light trapping programs would need very large numbers of lights that may, paradoxically, repel moths due to their collective intensity.

Australia’s use of remote sensing data is intended to allow Australia to identify the highest risk seaports in Asia, and when each seaport presents a risk of AGM contamination (Nielsen 2011). Our ultimate aim is to use our surveillance data alongside climate models to predict when individual risk seaports in Asia will become a risk for AGM. This information can then be used to design inspection programs that offer minimal disruption to international trade, an outcome aligned with provisions of the SPS agreement, to which Australia is signatory.

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**Appendix A: Pest categorisation for Lymantria species likely to be associated with maritime vessels**

| **Pest** | **Present in Asia**  | **Potential to be on MCV pathway** | **Present within Australia** | **Potential for establishment and spread** | **Potential for economic consequences** | **Quarantine pest on pathway** |
| --- | --- | --- | --- | --- | --- | --- |
| **Class: Insecta** |
| **Order: Lepidoptera (Butterflies and Moths)** |
| **Family Lymantriidae (Gypsy and Tussock Moths)** |
| *Lymantria dispar asiatica*Vnukovskij, 1926Asian gypsy moth | Yes. *L. dispar asiatica* occurs throughout temperate Asia east of the Ural Mountains. Its range includes Russia, Mongolia, the northern 2/3 of China, Mongolia and the Korean Peninsula (Pogue and Schaefer 2007). | Yes. Females are attracted to a range of lights and illuminated objects at night (Wallner et al. 1995) and can settle in large numbers on maritime cargo vessels (Ministry of Agriculture 2008; United States Department of Agriculture 2004). Egg masses of this taxon have been intercepted on vessels by quarantine authorities in New Zealand and the United States (Ministry of Agriculture 2008; United States Department of Agriculture 2004). | Not listed (Nielsen *et al.* 1996; Dominiak *et al.* 2006) | Yes. *Lymantria dispar* is a highly polyphagous insect feeding on at least 1300 plant species. The closely allied and partly sympatric *L. dispar dispar* has established and spread in parts of the United States (United States Department of Agriculture 2004; MAFNZ 2004). The closely related taxa *L. dispar dispar* and *L. umbrosa* have established populations in the United States and New Zealand, respectively (United States Department of Agriculture 2004; MAFNZ 2004). | In North America, the allied *L. dispar dispar* is a serious forest defoliator that has caused losses of approximately US$30 million per year since 1987. This cost considers both direct loss of production and interstate quarantine restrictions on forest products (WSDA 2007). *Lymantria dispar asiatica* could inflict similar damage if it were to establish in Australia, as many of its known hosts are mainstay species of timber production in Australia (Pogue and Schaefer 2007). | Yes |
| *Lymantria dispar japonica*(Motschulsky, 1860)Japanese gypsy moth | Yes. *L. dispar japonica* is endemic to the Japanese islands of Honshu, Shikoku, Kyushu and south-western areas of Hokkaido (Pogue and Schaefer 2007). | Yes. *Lymantria dispar japonica* egg masses have been intercepted on vessels by quarantine authorities in New Zealand and the United States (Ministry of Agriculture 2008; United States Department of Agriculture 2004).  | Not listed (Nielsen *et al.* 1996; Dominiak *et al.* 2006) | Yes. *Lymantria dispar* is a highly polyphagous insect feeding on at least 1300 plant species. The closely allied and partly sympatric *L. dispar dispar* has established and spread in parts of the United States (United States Department of Agriculture 2004; MAFNZ 2004). The closely related taxa *L. dispar dispar* and *L. umbrosa* have established populations in the United States and New Zealand, respectively (United States Department of Agriculture 2004; MAFNZ 2004). | Yes. *Lymantria dispar japonica* is known to cause economic loss in fruit cropping systems in Japan (Pogue and Schaefer 2007).In North America, the allied *L. dispar dispar* is a serious forest defoliator that has caused losses of approximately US$30 million per year since 1987. This cost considers both direct loss of production and interstate quarantine restrictions on forest products (WSDA 2007). | Yes |
| *Lymantria mathura*Moore, 1865Pink gypsy moth | Yes. *Lymantria mathura* occurs from Japan (all islands) and Siberia, Russia, southwards through Korea, China (including Taiwan) and west through Indochina into Vietnam, Thailand, Nepal, India and Sri Lanka. | Yes. *Lymantria mathura* has been intercepted several times by quarantine authorities in Canada and the United States.Despite having an insertion type ovipositor, *L. mathura* appears to change its egg-laying behaviour during outbreaks and may contaminate non-host objects. As females are attracted to lights at night, they may be attracted to and contaminate maritime cargo vessels (Pogue and Schaefer 2007). | Not listed (Nielsen *et al*. 1996) | Yes. *Lymantria mathura* is widely distributed from cold temperate to subtropical environments (Pogue and Schaefer 2007), which would aid its establishment throughout Australia south of the Tropic of Capricorn. It is a polyphagous species, exploiting both deciduous and non-deciduous angiosperms (Pogue and Schaefer 2007). Many of its hosts are widely cultivated in Australia as agricultural crops, garden and amenity plants. These attributes would likely allow *L. mathura* to establish and spread within Australia. | Yes. *Lymantria mathura* feeds on a range of plants grown for agriculture, amenity and gardens, including *Mangifera indica* and species of *Dimocarpus*, *Litchi*, *Malus*, *Pyrus*, *Prunus* and *Quercus*. *Lymantria mathura* larvae would cause economic damage through lost production and the cost chemical and cultural controls. As several hosts (e.g. *Mangifera indica*) are also widespread in gardens and amenity area, some control costs would be privately carried by the public. | Yes |
| *Lymantria monacha*(Linnaeus, 1758)Nun moth | Yes. *Lymantria* *monacha* is widespread throughout Eurasia, including China, the Korean peninsula and Japanese archipelago. It also occurs in Kazakhstan, Uzbekistan and Tajikistan. | Yes. Female *L. monacha* respond to lights and, although they have an insertion-type ovipositor (Pogue and Schaefer 2007), they are known to contaminate maritime cargo vessels (Kimoto and Duthie-Holt 2006). | Not listed (Nielsen *et al*. 1996) | Yes. *Lymantria monacha* is widespread through temperate Asia, parts of which have similar climate to some areas in southern Australia. Its host range includes many species used for agricultural, amenity and garden purposes (Pogue and Schaefer 2007). These attributes could aid the ability of *L. monacha* to establish and spread in Australia. | Yes. Many *L. monacha* feeds on plants grown for agriculture and gardens in Australia, including *Cydonia vulgaris*, *Malus domestica, Prunus armeniaca*, and species of *Quercus, Acer,* and *Betula* and *Rosa* grown for amenity.Establishment and spread of *L. monacha* would cause economic damage through lost production and chemical control in apple orchards, while infestations of amenity trees may also require chemical and cultural control. Damage to amenity and ornamental plants will incur a cost to the community in general. | Yes |
| *Lymantria umbrosa*(Butler, 1881)Hokkaido gypsy moth | Yes. *Lymantria umbrosa* is endemic to Japan (Hokkaido) and Russia (Kuril Islands, potentially Siberia) (Pogue and Schaefer 2007). | Yes. Female *L. umbrosa* are attracted to lights at night and may oviposit on non-hosts (Pogue and Schaefer 2007). As this species was previously considered a subspecies of *L. dispar*, it is likely that some interceptions attributed to *L. dispar* from Japan were in fact *L. umbrosa.* An incursion of this moth into New Zealand is believed to have originated from an egg mass arriving via maritime commerce (Ross 2005). | Not listed (Nielsen *et al*. 1996) | Yes. A male *L. umbrosa* trapped in New Zealand is believed to have originated from an egg mass imported via maritime commerce. This would require the moth to have undergone full development in New Zealand (Ross 2005).It is likely that *L. umbrosa* could establish and spread within southern temperate areas of Australia where suitable host plants also occur. | Yes. *Lymantria umbrosa* feeds on plants used as amenity trees and ornamental plants in Australian parks and gardens, and commercially valuable fruits (*Morus* and *Rubus* spp.). *Lymantria umbrosa* often defoliates large areas of suitable hosts in Japan (Pogue and Schaefer 2007). Control and management of this species in Australia in commercial fruit crops and plants in urban areas would be costly. | Yes |

**Appendix B Example risk assessment map generated using remote sensing techniques for Petropavlosk-Kamchatsky, Russian Federation.**



**Appendix C – Seaports found to be within 2000 metres of forested areas likely to support populations of Lymantria risk taxa by geospatial intelligence**

| **Country** | **Port Name** | **Country** | **Port Name** |
| --- | --- | --- | --- |
| China | Dandong | Russia (Far East) | Aleksandrovsk-Sakhalinsky |
| Dongshan | De-Kastri |
| Lianyungang | Kholmsk |
| Shanwei | Lazarev |
| Yangjiang | Magadan |
| Japan | Aioi | Nakhodkha |
| Fukuyama | Nevelsk |
| Hiroshima | Nikolaevsk on Amur |
| Imari | Olga |
| Kikuma | Petropavlovsk -Kamchatsky |
| Matsushima | Poronaysk |
| Mizushima | Posyet |
| Moji | Sovgavan(Sovetskaya Gavan) |
| Naha | Uglegorsk |
| Niigata | Ust Kamchatsk |
| Shimotsu | Vanino |
| Susaki | Vladivostok |
| Tachibana | Vostochny |
| Tamano | South Korea | Busan (Pusan) |
| Tsukumi | Donghae |
| North Korea | Chonjin | Gwangyang |
| Haeju | Masan |
| Hungnam | Mokpo |
| Nampo | Okgye |
| Sonbong | Pyeongtaek |
| Sonjin | Samcheok |
| Taiwan | Taichung | Ulsan |