MCM Modeling Forum

Results of the 2021 Mathematical Contest in Modeling

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Introduction

A total of 10,053 teams of undergraduates from hundreds of institutions and departments in 15 countries/regions spent a weekend working on applied mathematics problems in the 37th Mathematical Contest in Modeling (MCM).

This year's contest ran over a single weekend from Thursday, February 4 to Monday, February 8, 2021. During that time, teams of up to three undergraduate or high school students researched, modeled, analyzed, solved, wrote, and submitted their solutions to an open-ended real-world modeling problem. After a weekend of challenging and productive work, solution papers were sent to COMAP for judging. Seventeen of the papers were judged to be Outstanding by the panel of expert judges. Three of those submissions appear in this issue, one from each of the MCM problems, together with commentaries from the contest judges.

All of the competing teams are to be congratulated for their excellent work and enthusiasm for mathematical modeling and problem solving.

The Interdisciplinary Contest in Modeling (ICM), a companion contest, took place concurrently over the same weekend. The ICM offers modeling problems involving operations research and network science, sustainability, and policy modeling. Details about the 2021 ICM Contest and its results are in Vol. 42, No. 3 of this *Journal*.

The 2022 MCM Contest is scheduled to take place February 17–21, 2022.
The 2023 MCM Contest is scheduled to take place February 16–20, 2023.

The UMAP Journal 42 (4) (2021) 369–392.

Description of the Problems

This year's three MCM problems represented interesting scenarios for contestants, each offering a different dimension of mathematical modeling. All MCM problems were created by the MCM Problem Committee, a group of professional mathematical modelers from several academic organizations. This year's committee was comprised of:

- Committee Chair: Michael Tortorella
- Members: David Olwell, Kelly Black, Bill Bauldry, Keith Erickson, Steve Horton

The A Problem

The A problem required teams to predict the interactions between a wide variety of species of fungi and examine their role in decomposing ground litter and woody fibers. The results from a recent paper [Lustenhouwer et al. 2020] were provided to help teams determine the relative growth rates of various fungi within a number of different environments. Once the dynamics between fungi were established, teams were expected to provide predictions of the long- and short-term dynamics between the various species of fungi. This includes an examination of the impact of temperature fluctuations and variations of the fluctuations within each of a designated set of environments. The final question to examine was the role of biodiversity in the rate of decomposition of the system as a whole and how biodiversity was impacted by changes in the local environment.

Reference

Lustenhouwer, Nicky, Daniel S. Maynard, Mark A. Bradford, Daniel L. Lindner, Brad Oberle, Amy E. Zanne, and Thomas W. Crowther 2020. A trait-based understanding of wood decomposition by fungi. *Proceedings of the National Academy of Sciences of the United States* (13 May 2020). https://www.pnas.org/content/pnas/117/21/11551.full.pdf.

The B Problem

The B Problem was inspired by the devastating 2019–2020 fire season in Australia and by new investigations of the US Forest Service in fire fighting communication. Teams were given two types of drones with their capabilities: surveillance and situational-awareness drones and hovering drones carrying radio repeaters (to significantly extend hand-held radio range). Teams were to create a model optimizing the numbers and mixes of these drones for fire-fighting units. Teams were to show how their model would adapt to climate change induced increasing likelihood of extreme fire-event size and frequency. Teams were also required to develop a model to optimize locations of hovering drones for fires of differing sizes on differing terrain. Their final task was to prepare a short annotated budget request for the drones.

The C Problem

Problem C explored the recent proliferation of Asian giant hornets in Washington State. The state has solicited data from the public on a website about sightings of these hornets. In most of the reports, the public mistakes other insects for the Asian giant hornets. State entomologists have classified reports based on the text and images provided, a labor-intensive process. Teams were asked to develop a model that prioritizes reports from the public based on the likelihood that the input indicated an actual sighting. Teams were also asked to predict the spread of the pest in the state, based on the confirmed sightings and their models; determine how often to update their models; and to give model-based criteria for declaring that the pest had been eradicated. Their results were to be presented in a memorandum for the state Dept. of Agriculture.

Resources for Mathematical Modeling

COMAP's educational philosophy is centered on mathematical modeling to use mathematical concepts, methods, and tools to explore real-world problems. COMAP serves society by developing students as problem solvers in order to become better informed and prepared as citizens, contributors, consumers, workers, and community leaders. The MCM is an example of COMAP's efforts toward these goals.

COMAP's MCM and ICM are the only international modeling contests in which students work in teams.

In addition to this special issue of *The UMAP Journal*, COMAP offers at `http://www.mathmodels.org` the press releases for the 2021 contests, their results, their problems, unabridged versions of all the Outstanding papers, and judges' commentaries.

Results and winning papers from previous contests were published in special issues of *Mathematical Modeling* (1985–1987) and *The UMAP Journal* (1985–2020). The 1994 volume of *Tools for Teaching*, commemorating the 10th anniversary of the contest, contains the 20 problems used in the first 10 years of the contest and an Outstanding paper for each year. That volume and the special MCM issues of the *Journal* for the last few years are available from COMAP. The 1994 volume is also available on COMAP's special *Modeling Resource CD-ROM*. Also available is the *MCM @ 21 CD-ROM*, which contains the 20 problems from the second 10 years of the contest, an Outstanding paper from each year, and advice from advisors of Outstanding teams. These CD-ROMs can be ordered from COMAP at

http://www.comap.com/product/cdrom/index.html

Contest problems and results of the MCM/ICM contests are at

http://www.comap.com/undergraduate/contests

Mathematical Modeling for the MCM/ICM Contests Volume 1 exposits the ideas, background knowledge, and modeling methodologies for solving problems in the MCM/ICM contests. That volume also presents a brief history of the MCM/ICM contests, offers ideas to help students prepare for the contests, presents general modeling framework and methodologies, describes the judging procedure, explains how to write successful entries, and presents a sample scheduling of tasks during the contest. A number of exercise problems are included to help students understand the materials presented in the book. Details and ordering are at

http://www.comap.com/product/?idx=1465

Finally, COMAP also makes available three volumes of the *Mathematical Modeling Handbook* on CD-ROM (the first two volumes are also available in print). Details and ordering are at

http://www.comap.com/product/?idx=1467

COMAP also sponsors:

- The Interdisciplinary Contest in Modeling (ICM), noted above.
- The High School Mathematical Contest in Modeling (HiMCM), which offers high school students a modeling opportunity similar to the MCM. Further details are at

  http://www.comap.com/highschool/contests

2021 MCM Statistics

- 10,053 teams participated (with 16,059 more in the ICM)
- 4,487 Problem A (45%)
- 3,105 Problem B (31%)
- 2,461 Problem C (24%)
- 164 U.S. teams (2%)
- 8,889 foreign teams (98%), from 14 countries/regions:
  Australia, Canada, China, France, Germany, Hong Kong (SAR), India, Indonesia, Ireland, Malaysia, Mexico, Taiwan China, the United Kingdom, and Vietnam.

- 17 Outstanding Winners (<1%)
- 284 Finalist Winners (3%)
- 697 Meritorious Winners (7%)
- 2,414 Honorable Mentions (24%)
- 6,400 Successful Participants (64%)
- 26 Unsuccessful Participants (<1%)
- 204 Disqualified Teams (2%)
- 11 Not judged (entry corrupted) (<1%)

Caution: Cite Your Sources

A disappointing number of teams (204) were disqualified for plagiarism. The MCM expects contestants to be careful about doing their own work and attributing their resources and references to the original authors. Submitted papers are expected to be the team's own effort; and when others' data, methodology, figures, equations, models, or ideas are used, attribution must be carefully and clearly given to the sources. A large number of teams did not properly and completely document images copied from external sites.

- Direct use of words from a source absolutely requires the use of quotation marks and citation to the exact source of the quotation.
- Rephrasing a quotation from a source still demands citing the source.
- Changing just a few words in a quotation from a source does not make the result your own work; it is more honest to use the original quotation, inside quotation marks.
- Any "objects"—images, figures, photographs, tables, drawings, examples, and data sets—that are reproduced in the contest entry but were not created by the team during the contest must be accompanied by a citation to the specific source.
- If a source was found on the Internet, the URL for it should be given, along with any journal or other bibliographic information for print versions.
- All citations should be to *specific* physical pages or web pages, with full details in the References section of the contest entry.

Problem A: Fungi

The **carbon cycle** describes the process of the exchange of carbon throughout the **geochemical cycle** of the Earth, and is a vital component for life on the planet. Part of the carbon cycle includes the decomposition of compounds, allowing carbon to be renewed and used in other forms. One key component of this part of the process is the decomposition of plant material and woody fibers.

Some of the key agents in decomposing woody fibers are **fungi**. The authors of a recent research article on wood decomposition by fungi identified fungi traits that determine decomposition rates and also noted links between certain traits [Lustenhouwer et al. 2020]. In particular, the slow-growing strains of fungi tend to be better able to survive and grow in the presence of environmental changes with respect to moisture and temperature, while the faster-growing strains tend to be less robust to the same changes. A synopsis of this article can be found below.

These researchers examined a large number of traits associated with different fungi and their role in the decomposition of ground litter (dead plant material) and woody fibers. For this MCM Problem, you should focus on just two traits of a fungus: the growth rate of the fungus and the fungus's tolerance to moisture. Your primary goal is to model the decomposition of woody fibers in a given patch of land, and do so in the presence of multiple types of fungi breaking down woody fibers in the same area.

As you explore the relationship of the two traits of interest, growth rate and **moisture tolerance**, with the rate of decomposition, several questions may arise to include: Using these two traits, how do the different fungi interact and decompose ground litter in a fixed patch of land in different environments? Within these different environments, how will the decomposition be impacted over time as conditions vary? How do environmental changes and the variation in environmental change impact the long-term dynamics with respect to decomposition, as well as competition between fungi in a given environment? The estimation for the decomposition rates, given the growth rate, is shown in **Figure 1**. The estimation of the decomposition rates, given the relative moisture tolerance, is shown in **Figure 2**.

Requirements

Your paper should explore and address the following aspects.

- Build a mathematical model that describes the breakdown of ground litter and woody fibers through fungal activity in the presence of multiple species of fungi.
- In your model, incorporate the interactions between different species of fungi, which have different growth rates and different moisture tolerances as shown in **Figures 1** and **2**.

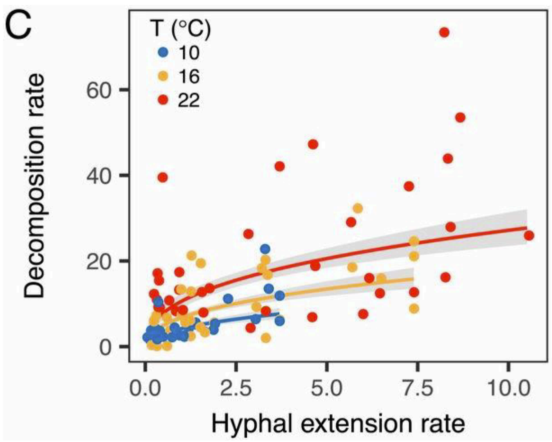

Figure 1. The relationship between the **hyphal extension rate** (mm/day) of various fungi and the resulting wood decomposition rate (% mass loss over 122 days) at various temperatures. (Figure 1C in Lustenhouwer et al. [2020]).

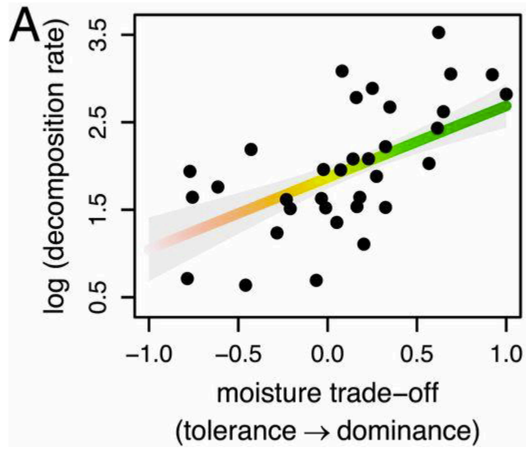

Figure 2. The relationship between the moisture tolerance (difference of each isolate's **competitive ranking** and its **moisture niche width**, both scaled to [0,1]) of various fungi and the resulting wood decomposition rate (% mass loss over 122 days, log transformed). (Figure 4A in Lustenhouwer et al. [2020]).

- Provide an analysis of the model and describe the interactions between the different types of fungi. The dynamics of the interactions should be characterized and described, including both short- and long-term trends. Your analysis should examine the sensitivity to rapid fluctuations in the environment, and you should determine the overall impact of changing atmospheric trends to assess the impact of variation of local weather patterns.
- Include predictions about the relative advantages and disadvantages for each species and combinations of species likely to persist, and do so for different environments including arid, semi-arid, temperate, arboreal, and tropical rain forests.
- Describe how the diversity of fungal communities of a system impacts the overall efficiency of the system with respect to the breakdown of ground litter. Predict the importance and role of biodiversity in the presence of different degrees of variability in the local environment.

Include a two-page article of your results. Your article should be appropriate for inclusion in an introductory college-level biology textbook to discuss recent developments in our understanding of the roles that fungi play in ecological systems.

Your PDF solution of no more than 25 total pages should include:

- One-page Summary Sheet.
- Table of Contents.

- Your complete solution.
- Two-page article.
- References list.

Note: The MCM Contest now has a 25-page limit. All aspects of your submission count toward the 25-page limit (Summary Sheet, Table of Contents, solution, Reference List, and any Appendices).

Reference

Lustenhouwer, Nicky, Daniel S. Maynard, Mark A. Bradford, Daniel L. Lindner, Brad Oberle, Amy E. Zanne, and Thomas W. Crowther 2020. A trait-based understanding of wood decomposition by fungi. *Proceedings of the National Academy of Sciences of the United States* (13 May 2020). https://www.pnas.org/content/pnas/117/21/11551.full.pdf.

Research Article Synopsis

We provide a brief synopsis below of the research article by Lustenhouwer et al. [2020]. Note that you do not need to read the original article to complete this MCM Problem.

The decomposition of organic material is a critical component of the **carbon cycle**. Large-scale modeling of the carbon cycle as well as global climate models are becoming more refined and are incorporating more small-scale details. One important detail is the rate associated with the decay of organic material by microbial and fungal communities. The focus of the paper is the different decay rates associated with different types of **fungi**.

The authors of the paper explored several different traits of fungi to determine the effects of the decomposition of wood. They did so by measuring how much mass was lost in wood blocks after introducing different types of fungi into the blocks. The researchers examined a large number of different traits associated with each fungus and attempted to determine the role these traits play in the decomposition of the wood blocks.

For example, one important trait is the **hyphal extension rate**. The **hyphae** are the cells that branch out and form the filaments and structure of a fungus, and the different kind of hyphae play different roles in the life cycle of a fungus. The hyphal extension rate is essentially the growth rate of a fungus. Another trait examined was the density of the hyphae in a given volume. These two traits are associated with a number of properties of a fungus. For example, it was found that if the hyphal extension rate was larger (faster growth), the fungus was more likely to decompose wood faster. Likewise, if the filaments were denser, it was more likely that the decomposition of wood was slower. Additionally, these two traits are also associated with how a fungus reacts to different environmental conditions.

In particular, the researchers found that fungi that were better able to adapt to a more varied range of moisture conditions tended also to decompose wood more slowly. Fungi that grew faster and out-competed other fungi tended to decompose wood faster. **Figures 1** and **2** in the MCM Problem A statement show these relationships.

Woody materials break down through multiple stages, and the fungi that were examined in the research article are most relevant with respect to the decay of woody materials in the middle of their decay cycle. The results may differ for other stages of decay. For the purpose of this modeling exercise, you can focus on the results for the middle stage and assume that it is consistent for other stages of decomposition. Another consideration is that local environmental conditions can vary greatly over an area and impact the overall dynamics as well.

Glossary

- **Biodiversity:** Broadly, the variety of life in the world. On a smaller scale, the variety of life in a particular habitat or ecosystem.
- **Carbon cycle:** The continuous process (or series of processes) by which carbon is exchanged between organisms and the environment, and then reused throughout the planet.
- **Competitive ranking:** A measure of the ability for a fungus to out-compete other fungi in a series of pairwise tests in similar conditions.
- **Earth's biosphere:** The lithosphere (crust and upper mantle of the Earth), the hydrosphere (all of the water on the Earth's surface), and the atmosphere (the envelope of gases surrounding the Earth) of the Earth.
- **Fungus (plural: fungi):** Any member of the group of eukaryotic (cells that have a nucleus enclosed within a nuclear envelope) organisms. Examples are yeasts, molds, and mushrooms.
- **Geochemical cycle:** The various pathways and steps by which elements are exchanged through and between the **Earth's biosphere**.
- **Hyphae (singular: hypha):** The cells that form the filaments within a fungal community.
- **Hyphal extension rate:** The rate of growth of a fungus.
- **Moisture niche width:** The difference between the maximum and minimum moisture levels in which half of a fungal community can maintain its fastest growth rate.
- **Moisture tolerance:** The difference between a fungus's competitive ranking and its moisture niche width.

Problem B: Fighting Wildfires

Background

The 2019–2020 fire season in Australia saw devastating wildfires in every state, with the worst impact in New South Wales and eastern Victoria. The wildfires occurred during a severe drought and persistent heat wave exacerbated by climate-change. **Figure 3** shows the wildfire hot spots in this area from October 1, 2019 to January 7, 2020, with yellow showing fires from October 1 to January 6, and red showing active fires on January 7, 2020.

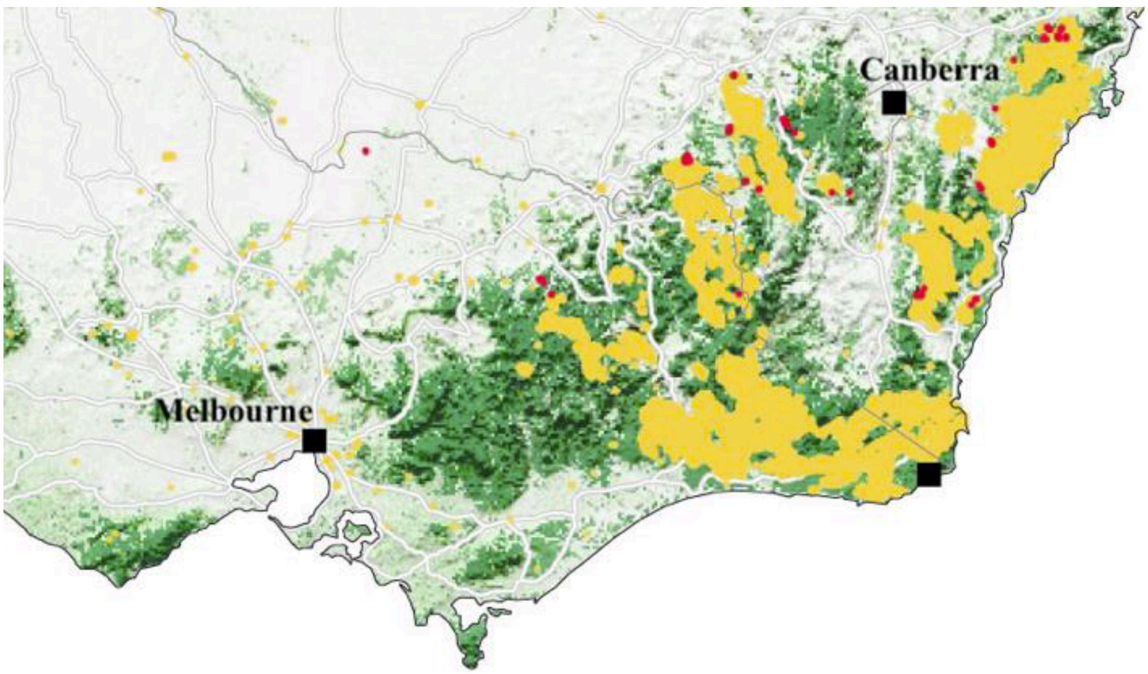

Figure 3. Wildfire hotspots in Southeast Australia, Oct 1, 2019 to Jan 7, 2020. Source: Australian Government Bureau of Meteorology, NASA Fire Information for Resource Management System.

Firefighters have used drones for **surveillance** and **situational awareness** (SSA) for several years; SSA drones carry high definition and thermal imaging cameras and telemetry sensors that monitor and report data from wearable devices on front-line personnel. Wearable devices can be used as Personal Locator Beacons or more complex environmental monitors. SSA drones help monitor the evolving situation, letting the **Emergency Operations Center (EOC)** best direct active crews for optimal effect and maximal safety.

Two-way radio communication allows **"boots-on-the-ground" forward teams** to give status reports to the EOC and allows the EOC to give orders directly to forward teams. Deployed personnel carry handheld two-way radios operating in the VHF/UHF bands. The range of handheld radios is limited by their low transmitting power, typically a maximum of 5 watts, and is determined mainly by distance and physical topography in rural areas or by "building topography" in urban areas; weather has little effect on VHF/UHF signals. A 5-watt radio has a nominal range of 5 km over flat unobstructed ground but the range drops to 2 km in an urban area. **Repeaters**, **transceivers** that automatically rebroadcast signals at higher powers, can extend radio range. A repeater located between the front lines and the EOC can relay radio signals both from the front lines to the EOC and from the EOC to the front lines. The range of a repeater is also determined by distance and topography but is significantly greater than lower-power handheld radios.

Recently, hovering drones carrying repeaters have been used to dramatically extend the range of low-power radios on the front lines. A 10-watt repeater, weighing 1.3 kg and carried by a drone hovering well above ground level, can achieve a range of 20 km. Akme Corporation's prototype WileE–15.2X hybrid drone is projected to cost approximately $10,000 (AUD) when equipped with either a radio repeater or video and telemetry capability. Tests have shown that this drone has the capabilities listed in **Table 1**.

Table 1.

WileE–15.2X Hybrid Drone capabilities.

Flight range	Maximum speed	Maximum flight time
30 km	20 m/s	2.50 hr

1.75 hour recharge time for the built-in battery.
Note: Auxiliary batteries for radios or video/telemetry can be swapped while the built-in battery recharges.

Requirements

Your team of consultants has been retained to:

1. Create a model to determine the optimal numbers and mix of SSA drones and Radio Repeater drones to purchase for a proposed new division, "Rapid Bushfire Response," of Victoria's Country Fire Authority (CFA). Your model should balance capability and safety with economics, as well as consider observational and communications mission needs and topography. Your model should also incorporate fire-event size and frequency as parameters.

2. Illustrate how your model adapts to the changing likelihood of extreme fire events over the next decade. Project what equipment cost increases will occur assuming the cost of drone systems stays constant.

3. Determine a model for optimizing the locations of hovering VHF/UHF radio-repeater drones for fires of different sizes on different terrains such

as those shown in **Figure 4**, a topographical map of Eastern Victoria. Note that elevations range from sea level at the coast to 1,986 m at Mt. Bogong, Victoria.

Figure 4. Topographical map of Eastern Victoria. Source: www.freeworldmaps.net.

4. Prepare a one- to two-page annotated budget request supported by your models for CFA to submit to the Victoria State Government.

Your PDF solution of no more than 25 total pages should include:

- One-page Summary Sheet.
- Table of Contents.
- Your complete solution.
- One- to two-page annotated Budget Request.
- References list.

Note: The MCM Contest now has a 25-page limit. All aspects of your submission count toward the 25 page limit (Summary Sheet, Table of Contents, solution, Reference List, and any Appendices).

Glossary

- **"Boots-on-the-ground" forward teams:** "Boots on the ground" indicates personnel that are physically at the location of action. In firefighting, these are teams at the front lines of the efforts to control a fire event; they have immediate critical knowledge of the rapidly-changing situation.
- **Budget request:** A budget request is a business letter seeking funds for costs, expenses, and/or operating overhead for a project or department within an organization. An annotated budget request provides a justification or rationale for each requested item.
- **Country Fire Authority (CFA):** A volunteer fire service responsible for fire suppression, rescues, and response to other accidents and hazards across most of the state of Victoria, Australia
- **Emergency Operations Center (EOC):** The central command and control point for emergency-related operations and activities, and for requests for activation and deployment of resources (personnel or equipment). A mobile EOC can be deployed near the site of an emergency.
- **Repeater:** An unattended radio transceiver that automatically rebroadcasts a received signal at high power on a nearby frequency ($\sim$600 kHz (0.6 MHz) for VHF and $\sim$5 MHz for UHF) or on an adjacent channel.
- **Situational awareness:** The perception of the current elements of an event, understanding their significance, and extrapolating their status to the near future; in other words, the knowledge and understanding of what is going on around you.
- **Surveillance:** The systematic collection and analysis of data, and the sharing of those data to others who can act upon that information.
- **Transceiver:** A radio that can both transmit and receive.
- **UHF (Ultra High Frequency):** Radio frequencies from 300 to 3,000 MHz.
- **VHF (Very High Frequency):** Radio frequencies from 30 to 300 MHz.

Problem C: Confirming the Buzz about Hornets

In September 2019, a colony of *Vespa mandarinia* (known popularly as the Asian giant hornet) was discovered on Vancouver Island in British Columbia, Canada. The nest was quickly destroyed, but the news of the event spread rapidly throughout the area. Since that time, several confirmed sightings of the pest have occurred in neighboring Washington State, as well as a multitude of mistaken sightings. See **Figure 5** for a map of detections, hornet watches, and public sightings.

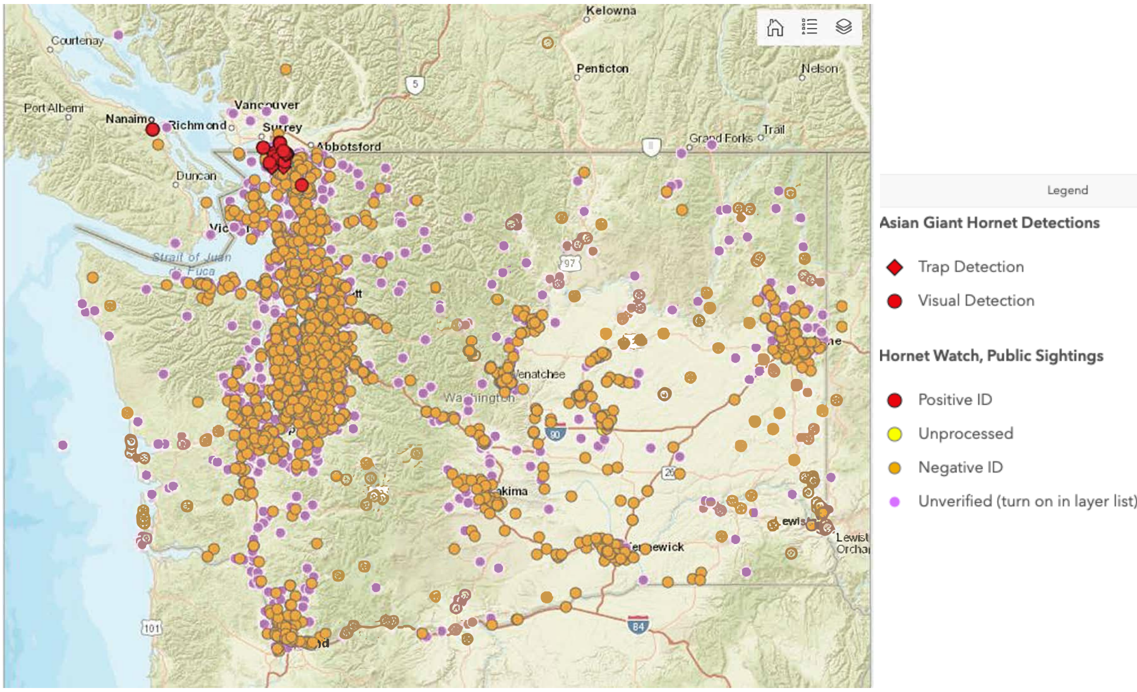

Figure 5. Map depicting Asian giant hornet detections, as well as Hornet Watch and public sighting locations.

Vespa mandarinia is the largest species of hornet in the world, and the occurrence of the nest was alarming. Additionally, the giant hornet is a predator of European honeybees, invading and destroying their nests. A small number of the hornets are capable of destroying a whole colony of European honeybees in a short time. At the same time, the hornets are voracious predators of other insects that are considered agricultural pests.

The life cycle of this hornet is similar to many other wasps. Fertilized queens emerge in the spring and begin a new colony. In the fall, new queens leave the nest and will spend the winter in the soil waiting for the spring. A new queen has a range estimated at 30 km for establishing her nest. More detailed information on Asian hornets is included in the problem attachments and can also be found online.

Due to the potential severe impact on local honeybee populations, the presence of *Vespa mandarinia* can cause a good deal of anxiety. The State of Washington has created helplines and a website for people to report sightings of these hornets. Based on these reports from the public, the state must decide how to prioritize its limited resources to follow-up with additional investigation. While some reports have been determined to be *Vespa mandarinia*, many other sightings have turned out to be other types of insects.

The primary questions for this problem are:

- How can we interpret the data provided by the public reports?, and
- What strategies can we use to prioritize these public reports for additional investigation, given the limited resources of government agencies?

Your paper should explore and address the following aspects:

- Address and discuss whether or not the spread of this pest over time can be predicted,and with what level of precision.
- Most reported sightings mistake other hornets for the *Vespa mandarinia*. Use only the data set file provided, and (possibly) the image files provided, to create, analyze, and discuss a model that predicts the likelihood of a mistaken classification.
- Use your model to discuss how your classification analysis leads to prioritizing investigation of the reports most likely to be positive sightings.
- Address how you could update your model given additional new reports over time, and how often the updates should occur.
- Using your model, what would constitute evidence that the pest has been eradicated in Washington State?

Finally, your report should include a two-page memorandum that summarizes your results for the Washington State Dept. of Agriculture.

Your PDF solution of no more than 25 total pages should include:

- One-page Summary Sheet.
- Table of Contents.
- Your complete solution.
- Two-page Memorandum.
- References list.

Note: The MCM Contest now has a 25-page limit. All aspects of your submission count toward the 25-page limit (Summary Sheet, Table of Contents, solution, Reference List, and any Appendices). You should not make use of unauthorized images and materials whose use is restricted by copyright laws. Ensure that you cite the sources for your ideas and the materials used in your report.

General Guidelines for Problem C

In addition to the specific requirements listed above, please keep in mind that this is a statistical modeling exercise. Submissions are expected to adhere to best practices associated with the use of data. Some examples of these expectations include but are not limited to the following:

- Define all metrics and cost functions that you use.
- Any estimate of a parameter should include an interval estimate.
- Any result should include estimates with respect to the goodness of fit of the results.
- All assumptions should be clearly stated, especially with respect to distributions associated with the data or errors.
- All assumptions associated with the data should be checked, and the robustness of a technique with respect to those assumptions should be examined.
- All assumptions associated with an approach or technique should be clearly stated.

Attachments

We provide the four following materials for this problem. THE DATA FILES PROVIDED CONTAIN THE ONLY DATA YOU SHOULD USE FOR THIS PROBLEM. General background data, such as that found in an atlas, an encyclopedia, or other standard reference may be used if documented. This might include elevation, climate, or other information. Additional data from Washington State on Asian hornets similar to what was provided in the spreadsheet is explicitly not allowed; in particular, adding additional observations from the state website is prohibited. A reasonable number of additional and documented images to assist in training an algorithm is allowed, similar to how dictionary data was allowed in the text analysis problem last year. Contestants should explicitly explain where they got the information and how it was used.

1. `2021MCM_ProblemC_Vespamandarinia.pdf`
   Background information from Pennsylvania State University Extension that describes the insect.
2. `2021MCM_ProblemC_DataSet.xlsx`
   A spreadsheet with 4,440 reports of sightings with the following fields:
   - **GlobalID**: a unique label for each sighting record.
   - **Detection Date**: the reported date of the sighting.
   - **Notes**: comments provided by the person submitting the report. This can be a member of the public, or occasionally a state employee.
   - **Lab Status**: the official classification of the sighting by the State Dept. of Agriculture after analysis.
     - *Positive ID* means that it is confirmed as an Asian giant hornet.
     - *Negative ID* means it is excluded.

  - *Unprocessed* means it has not yet been classified.
  - *Unverified* means no determination was made due to lack of information.
- **Lab Comments**: what the state entomology lab added to the record after analysis.
- **Submission Date**: the date the report was made to the state. This date can be significantly after the detection date.
- **Latitude (of sighting)**: these data are provided by the state after converting the address provided by the report.
- **Longitude (of sighting)**: these data are provided by the state after converting the address provided by the report.

3. `2021MCM_ProblemC_Files.rar`
   A `rar` file (663 MB) with 3,305 images submitted with the sighting reports. A password is required to open the file:

   `Af6SP7rdm33PxPJmDb4wZq7cw`

4. `2021MCM_ProblemC_Images_by_GlobalID.xlsx`
   A spreadsheet mapping the images to the sightings with the following fields:
   - **FileName**: the name of an image in the `rar` folder.
   - **GlobalID**: a unique label for each sighting record. This is consistent across the two spreadsheets.
   - **FileType**: Images arrive as .jpg, .pdf, .png, .jfif, octet-stream, xml open format, or .zip files. Videos arrive as .mp4 or quicktime files.

EDITOR'S NOTE: The above files are available for download at
http://www.mathmodels.org/Problems/2021/MCM-C/2021_MCM_Problem_C_Data.zip
and
https://www.comap-math.com/mcm/2021MCM_ProblemC_Files.rar

Reference

Washington State Department of Agriculture. 2020 Asian Giant Hornet Public Dashboard. https://agr.wa.gov/departments/insects-pests-and-weeds/insects/hornets/data. Accessed 11/5/2020.

The Results

Solution papers are coded at COMAP headquarters so that names and affiliations of the authors are unknown to the judges. Each paper is then read preliminarily by two "triage" judges at a triage session site. At each triage site, two time-limited comprehensive readings of each paper take place in comparison to a set of scoring criteria that establish minimum and maximum point allocations against a standard baseline. The scoring criteria are created by each problem's Head Judge in collaboration with the Contest Director and subsequently distributed to each triage site prior to the start of judging. These point allocations, in concert with established MCM quality elements, determine a paper's positioning within the overall pool of submissions for a particular problem. In the case that two triage judges' scores on a paper differ by more than 3 points, a third judge scores the paper.

The judges classified the papers as shown in the table below.

	Outstanding	Finalist	Meritorious	Honorable Mention	Successful Participation	Unsuccessful	Disqualified	Total
Problem A	6	67	322	1,249	2,691	21	125	4,487
Problem B	5	103	195	665	2,065	4	65	3,105
Problem C	6	114	180	500	1,644	1	14	2,461
	17	284	697	2,414	6,400	26	204	10,053

We list the 17 Outstanding teams, together with 3 Finalist teams that won awards; the list of all participating schools, advisors, and results is at the COMAP Website.

Outstanding Teams and Awardees

- Problem A (Fungi Problem)
  - Beijing Institute of Technology, Beijing, China
    (Ben Fusaro Award)
  - Central South University, Hunan, China
    (INFORMS Award)
  - Chongqing University, Chongqing, China
  - Jiangnan University, Jiangsu, China
  - Rensselaer Polytechnic Institute, New York, USA (Finalist)
    (MAA Award)
  - Shanghai Jiao Tong University, Shanghai, China
    (SIAM Award, COMAP Scholarship Award)
  - University of Electronic Science and Technology of China,
    Sichuan, China (AMS Award)

- Problem B (Fighting Wildfires Problem)
  - Beihang University, Beijing, China (Finalist)
    (INFORMS Award)
  - Hohai University, Nanjing, China
  - Nanjing University of Posts & Telecommunications, Jiangsu, China
    (Frank Giordano Award, SIAM Award)
  - National University of Defense Technology, Hunan, China
  - University of Colorado Boulder, Colorado, USA
    (Finalist) (MAA Award)
  - Xi'an Jiaotong University, Shaanxi, China
    (AMS Award)
  - Xidian University, Shaanxi, China
- Problem C (Giant Hornet Problem)
  - Beijing Jiaotong University, Beijing, China
    (ASA Award)
  - Shanghai Jiao Tong University Team 2101166, Shanghai, China
  - Shanghai Jiao Tong University Team 2101587, Shanghai, China
  - Soochow University, Jiangsu, China
  - University of Colorado Boulder, Colorado, USA
    (MAA Award, SIAM Award, COMAP Scholarship Award)
  - University of Oxford, Oxford, UK
    (INFORMS Award, AMS Award)

Awards and Contributions

Each participating MCM advisor and team member received a certificate signed by the Contest Director and the appropriate Head Judge.

INFORMS

INFORMS, the Institute for Operations Research and the Management Sciences, recognized three teams as INFORMS Outstanding teams. The teams were from

- Central South University, Hunan, China (Fungi Problem)
- Beihang University, Beijing, China (Fighting Wildfires Problem)
- University of Oxford, Oxford, UK (Giant Hornet Problem)

Society for Industrial and Applied Mathematics

The Society for Industrial and Applied Mathematics (SIAM) designated three Outstanding teams as SIAM Winners, from

- Shanghai Jiao Tong University, Shanghai, China (Fungi Problem)
- Nanjing University of Posts & Telecommunications, Jiangsu, China (Fighting Wildfires Problem)
- University of Colorado Boulder, Colorado, USA (Giant Hornet Problem)

Mathematical Association of America

The Mathematical Association of America (MAA) designated three North American teams as MAA Winners. The teams were from

- Rensselaer Polytechnic Institute, Troy, New York (Fungi Problem)
- University of Colorado Boulder Team 2100829, Colorado, USA (Fighting Wildfires Problem)
- University of Colorado Boulder Team 2107870, Colorado, USA (Giant Hornet Problem)

Each team member was presented a certificate by an official of the MAA Committee on Undergraduate Student Activities and Chapters.

Ben Fusaro Award

One Meritorious, Finalist, or Outstanding paper is selected for the Ben Fusaro Award, named for the Founding Director of the MCM and awarded for the 17th time this year. It recognizes an especially creative approach; details concerning the award, its judging, and Ben Fusaro are in Vol. 25 (3) (2004): 195–196. The Ben Fusaro Award Winner was from

- Beijing Institute of Technology, Beijing, China (Fungi Problem)

Frank Giordano Award

For the 8th time, the MCM is designating a paper with the Frank Giordano Award. Having worked on the contest since its inception, Frank Giordano served as Contest Director for 20 years.

This award goes to a paper that demonstrates a very good example of the modeling process in a problem featuring discrete mathematics. The Frank Giordano Award went to

- Nanjing University of Posts & Telecommunications, Jiangsu, China (Fighting Wildfires Problem)

ASA Data Insights Award

The American Statistical Association (ASA) selected a paper based on informative data visualizations, data modeling that was appropriate for the data and quantified uncertainty, validating predictions using external data, and overall quality of narrative and communication. The winner was the team from

- Beijing Jiaotong University, Beijing, China (Giant Hornet Problem)

The International COMAP Scholarship Award

The 3rd Annual International COMAP Scholarship Awards went to the Outstanding teams from

- Shanghai Jiao Tong University, Shanghai, China (Fungi Problem)
- University of Colorado Boulder Team 2107870, Colorado, USA (Giant Hornet Problem)

They each received $10,000 per team, with $9,000 going to the team members and $1,000 to the school, in the name of the advisor.

American Mathematical Society

The American Mathematical Society Award recognized the teams from

- University of Electronic Science and Technology of China, Sichuan, China (Fungi Problem)
- Xi'an Jiaotong University, Shaanxi, China (Fighting Wildfires Problem)
- Beijing Jiaotong University, Beijing, China (Giant Hornet Problem)

Judging

Director
Steven B. Horton, Professor Emeritus, Mathematical Sciences,
US Military Academy, West Point, NY
Associate Director
William C. Bauldry, Chair-Emeritus, Mathematical Sciences,
Appalachian State University, Boone, NC

Fungi Problem (A)

Head Judge
Kelly Black, Mathematics, University of Georgia, Athens, GA
Associate Judges
Joanna Bieri, Mathematics and Computer Science,
University of Redlands, Redlands, CA
Karen Bolinger, Mathematics, Clarion University, Clarion, PA
Thomas Fitzkee, Mathematics, Francis Marion University, Florence, SC
Jerry Griggs, Mathematics, University of South Carolina, Columbia, SC
Paul Heiney, Mathematics, US Military Academy Preparatory School,
West Point, NY
Christine Sample, Mathematics, Emmanuel College, Boston, MA
Elizabeth "Libby" Schott, Mathematics,
Florida Southwestern State College, Fort Myers, FL
Guangming Yao, Mathematics, Clarkson University, Potsdam, NY
Sofya Zaytseva, Mathematics, University of Georgia, Athens, GA

Fighting Wildfires Problem (B)

Head Judge
Robert Burks, Defense Analysis, Naval Postgraduate School,
Monterey, CA
Associate Judges
Tim Elkins, Systems Engineering, US Military Academy, West Point, NY
William P. Fox, Computational Operations Research,
College of William and Mary, Williamsburg, VA
Kerry Moores, Defense Analysis, The Joint Staff, Suffolk, VA
Kathleen Shannon, Mathematics, Salisbury University, Salisbury, MD
Dan Solow, Weatherhead School of Management,
Case Western Reserve University, Cleveland, OH
Rich West, Emeritus Professor of Mathematics, Francis Marion University,
Florence, SC
Bill Wilhelm, Lockheed Martin Corporation, Huntsville, AL
Daniel Zwillinger, BAE Systems, Burlington, MA

Giant Hornet Problem (C)

Head Judge
David H. Olwell, Professor and Dean, Hal and Inge Marcus School of Engineering, Saint Martin's University, Lacey, WA
Associate Judges
Mark Arvidson, Mathematics, Physics, and Statistics, Azusa Pacific University, Azusa, CA
Patrick J. Driscoll, Systems Engineering, US Military Academy, West Point, NY
James Enos, Systems Engineering, US Military Academy, West Point, NY
Stacey Hancock, Statistics, Montana State University, Bozeman, MT
Veena Mendiratta, Network Reliability and Analytics Researcher, Northwestern University, Evanston, IL
Greg Mislick, Operations Research, Naval Postgraduate School, Monterey, CA
Scott T. Nestler, Mendoza College of Business, University of Notre Dame, Notre Dame, IN
Carol Overdeep, Naval Undersea Warfare Center Division Keyport, Keyport, WA
Karen Richey Mislick, Operations Research, Naval Postgraduate School, Monterey, CA
Rodney Sturdivant, Statistical Science, Baylor University, Waco, TX

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Finally, we thank, for their involvement and unflagging support, the final judges, the more than 300 triage judges, and the MCM Board members, as well as the advisors to the teams.

Final Thoughts

To the reader of research journals:

Usually a published paper has been presented to an audience, shown to colleagues, rewritten, checked by referees, revised, and edited by a journal editor. Each paper here is the result of undergraduates working on a problem over a weekend. Editing (and usually substantial cutting) has taken place: Minor errors have been corrected, wording has been altered for clarity or economy, citations and references have been verified, and style has been adjusted to that of *The UMAP Journal*. The student authors have proofed the results. Please peruse these students' efforts in that context.

To the potential MCM advisor:

It might be overpowering to encounter such output from a weekend of work by a small team of undergraduates, but these solution papers are highly atypical. A team that prepares and participates will have an enriching learning experience, independent of what any other team does.

About the Author

Steven B. Horton is Professor Emeritus at the US Military Academy, West Point, NY. Prior to his retirement, he was Professor and Head of the Dept. of Mathematical Sciences there, as well as Chair of the Academy's Credentials and Promotions Committee, and Faculty Athletic Representative to the NCAA. He is a co-author of *A First Course in Mathematical Modeling* (5th ed., Cengage Learning, 2013), as well as dozens of technical papers. He earned an M.S.O.R. and a Ph.D. in Industrial and Systems from Georgia Tech and an M.S. in National Resource Strategy from the Industrial College of the Armed Forces. Rumors that he owns too many guitars are obviously untrue. He lives in Las Vegas, where he enjoys tennis, golf, and duplicate bridge.