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OPINION
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The Many Roles of Remote Sensing in Invasion Science

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INTRODUCTION

The large-scale redistribution of species and the global homogenization of the Earth's biota are amongst the most striking fingerprints of the Anthropocene (Kueffer, 2017). Invasions by alien species are a growing factor determining ecosystem functioning and reshaping local livelihoods and human well-being worldwide (Shackleton et al., 2019). The consequences of invasive alien species on human health, biodiversity, ecosystem services and livelihoods have been recognized by the United Nations' Sustainable Development Goals (SDG)—through SDG 15 -, and by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)—through their newly launched "thematic assessment on invasive alien species."

Nevertheless, biological invasions continue to rise alongside many rapidly changing events of the modern human epoch, such as the intensification of transportation networks, land system changes, technology, geopolitical events, and climate change (among others; Essl et al., 2017; Seebens et al., 2017). In order to better anticipate invasions and minimize the risks and damages posed by alien species, the scientific community has claimed for adjustments in the course of invasion science (e.g., Essl et al., 2017; Ricciardi et al., 2017; Vaz et al., 2017). For instance, recent horizon scans in invasion science (Ricciardi et al., 2017; Dehnen-Schmutz et al., 2018) identify and describe emerging biotechnological, ecological and sociopolitical challenges and opportunities that may (re)shape invasion science in the near future.

In this opinion essay, we come to stimulate thought and incite further research on the usefulness of remote sensing to tackle the emerging challenges and opportunities ahead of invasion science and management. Remote sensing can be broadly defined as the process of capturing information about an object without contacting it directly. It can be used to gather information about the Earth's systems through remote sensors (mounted on-board satellites, drones or even humans) and supplementary surveying techniques. Remote sensing has become increasingly relevant for environmental and (social-)ecological monitoring (Murray et al., 2018), and remote sensing data and tools are more accessible and abundant than ever, giving rise to "ecology's remote sensing revolution" (Kwok, 2018).

Over the last decade, remote sensing has offered many important contributions to the progress of invasion science, improving our understanding of the drivers, processes, patterns, and impacts of invasive species (e.g., Juanes, 2018; see Vaz et al., 2018 for a review). Remote sensing has been particularly useful to identify and map animal and plant invaders (Müllerová et al., 2017; Safonova et al., 2019) as well as to predict their current and future potential distributions and impacts (Rocchini et al., 2015; Hellmann et al., 2017). Remote sensing applications have been rapidly developing in the arena of invasions, and as technology evolves it is also becoming a prominent tool to manage alien species (and invaded areas) and their impacts (Vaz et al., 2018, 2019).

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Given the tremendous progress of remote sensing and the recent course traced for invasion science (Ricciardi et al., 2017; Dehnen-Schmutz et al., 2018), in the following sections we briefly discuss the relevance of remote sensing for tackling some of the key issues ahead of invasion science. Our narrative intends to promote the many roles of remote sensing in invasion science, by focusing on those particular issues for which remote sensing has become a valuable asset, namely in the following arenas: (1) biotechnology, associated to the emergence of novel invaders in modern agriculture and forestry; (2) invasion ecology, including the rapid expansion of invasive species and soil biota feedbacks in invaded ecosystems; and (3) sociopolitical interface, focusing on globalization factors promoting invasive species and on citizen science contributions for the management of invasions.

BIOTECHNOLOGY: NOVEL INVADERS ASSOCIATED TO AGRICULTURE AND FORESTRY

Industrial agriculture and forestry have fostered the recurrent introduction of alien species worldwide, leading to higher propagule pressures and invasion risks. Alongside these activities there is also an increasing transfer of pathogens, weeds and insect pests (Bufford et al., 2016). Remote sensing has developed into a variety of applications in modern agriculture and forestry (Mulla, 2013). These applications range from the mapping of weeds and the detection and monitoring of pests, to the assessment of crop quality against stress factors (Seelan et al., 2003; Thorp and Tian, 2004). The use of LiDAR technology (e.g., Riegl laser scanner) and hyperspectral sensors, either on satellites (e.g., ALI in EO-1 Hyperion), airborne vehicles (e.g., CASI sensor), or hand/boom-mounted structures (e.g., CropScan) has been particularly useful (Mulla, 2013). Another example includes the use of thermographic imaging techniques in agroforestry to detect nests of the invasive Asian hornet (*Vespa velutina*; Kennedy et al., 2018).

Remote sensing can be an effective tool to detect alien weeds (e.g., alien herbs and shrubs), pests and diseases (e.g., insects) at cultivation sites. The identification of feeding disturbances provoked by the Russian wheat aphid (*Diuraphis noxia*) on wheat (*Triticum* sp.) is an example (Mirik et al., 2014). Other examples exist for the detection of weed infestations (e.g., Thorp and Tian, 2004; Safonova et al., 2019). Also, when included in statistical modeling approaches (Leitão and Santos, 2019), remote sensing data can be used to detect species able to escape from cultivation sites and predict their potential areas of invasion. An example can be found on the invasive tree *Acacia dealbata*, for which the use of remote sensing data can aid not only the detection but also the prediction of potentially invaded areas (Vicente et al., 2016). Especially when involving time-series analysis remote sensing data can serve to monitor pests' impacts on the quality of cultivated species (e.g., Stone and Mohammed, 2017), or even the success of biocontrol actions on the management of invasive species (e.g., Bedford et al., 2018).

INVASION ECOLOGY: RAPID EXPANSIONS AND SOIL BIOTA FEEDBACKS

Alien species may experience fast expansions after lag times (Crooks, 2005), constituting one of the most challenging ecological issues ahead of invasion science (Ricciardi et al., 2017). These sudden invasions may occur due to changes in the inherent invasiveness of alien species (e.g., genetic alterations). Recent advances in the remote sensing arena have contributed to our understanding of the rapid evolutionary change of alien invaders. Examples come from precision agriculture, in which approaches combining genotyping, phenotyping, and hyperspectral information (e.g., UAV-based or boom-mounted) have been emerging to better navigate the genetic implications of species cultivation (Tattaris et al., 2016). Sudden invasions can (also) emerge due to rapid changes in invasibility and in response to external environmental factors (e.g., land conversion, climate change; Dehnen-Schmutz et al., 2018). Remote sensing can contribute to the anticipation and prediction of these rapid invasions by monitoring the environmental context in which they occur. Examples include the use of remote sensing to assess alien species' ecological requirements (Le Louarn et al., 2017) and monitor the state of essential environmental variables (such as Essential Biodiversity Variables; Pereira et al., 2013), allowing the anticipation and early-warning of critical thresholds and transitions in the environment in which alien species occur (Jetz et al., 2019).

Understanding feedbacks between soil biota and alien species has also been emerging as a pressing issue in invasion ecology (Putten et al., 2016; Ricciardi et al., 2017). The field of soil remote sensing has been progressing greatly over the last decades (see e.g., the special issue from Zribi et al., 2011). Modern remote sensing offers many approaches to monitor soil parameters, including texture (through hyperspectral sensors), surface temperature (using thermal infrared bands), moisture (via passive microwaves) and roughness (using active sensors like synthetic radar or scatterometer sensors; Zribi et al., 2011; Mulla, 2013). When properly calibrated with field measurements and applied in well-adjusted models, remotely sensed soil indices can provide fine-scale (and almost real-time) information on belowground-aboveground interactions (Mulder et al., 2011). For instance, based on hyperspectral reflectance, Carvalho et al. (2012) were able to show that soil biota contributed more to the content of defense compounds in the alien *Senecio inaequidens* than in native *S. jacobaea*.

SOCIOPOLITICAL INTERFACE: GLOBALIZATION OF INVASION RISKS AND PUBLIC PARTICIPATION

Current dynamics in trade agreements, transportation networks, migrations (and geopolitical conflicts) and land system reconfigurations are expected to intensify the displacement of species across distant regions and seas (Seebens et al., 2017). Remote sensing data can offer input variables to feed predictive models that are able to inform on invasion requirements and support early warning systems (Le Louarn et al., 2017), contributing as well to vulnerability analyses and damage assessments (Vicente et al., 2013, 2016). Examples derive from wider conservation ecology approaches and include the acquisition of information about spatial and temporal environmental variations that affect animal movements (Pettorelli et al., 2014) or remotely sensed observations of the quality of movement corridors (Wegmann et al., 2014), based on key factors such as net primary productivity or topography (Bohrer et al., 2012).

Moreover, the adoption of sensors to obtain information on human geography, urban sprawl, social war and conflicts (e.g., Fang and Jawitz, 2018) also reveals novel opportunities to inform on potential pathways of species introductions and invasions. Examples include the use of night-time light satellite imagery to identify human demographic patterns that influence species behaviors (e.g., Mazor et al., 2013) or the use of satellite radar information to detect marine traffic (Marino et al., 2015) that can lead to species displacement across seas.

As technology evolves and the social sphere becomes more solution-oriented, the possibilities of remote sensing at the interface between ecology and human geography are also attractive for invasion science (Dehnen-Schmutz et al., 2018). The increasing public access to drones and the availability of big data from social media (e.g., Facebook, Twitter, Instagram), combined with widely available remote sensing data, can provide detailed insights on invasions at unprecedented spatial and temporal resolutions. In fact, capitalizing citizen science approaches for the participatory sensing of invasions could constitute a step-ahead in the early detection, surveillance, and management of invasive species (Roy et al., 2018). The creation of programs and repositories for citizen science surveillance based on remote information (including mobile applications to receive and share information about invasive alien species, such as "invasoras.pt" or "planttracker.org.uk") could constitute a promising approach in the future of invasion science and management.

CONCLUDING REMARKS AND FUTURE PERSPECTIVES

There are still many challenges in the remote sensing arena, from those related to spatial, temporal, and spectral resolution to those dealing with data accessibility, processing and storage. Nevertheless, the future of remote sensing will offer more opportunities in the science of invasions, namely through easier access to advanced remote sensors, computational platforms, and remote sensing data. The resulting insights will refine our capacity to predict, detect and assess invasive species' occurrences, distributions, risks, and impacts.

Expected improvements comprise higher availability of multispectral optical imagery with increasing spatial, spectral and temporal resolutions, based on new satellites and sensors from public agencies (e.g., Landsat-8, Sentinel-2, EnMap) and private enterprises (e.g., Digital Globe, Planet Labs, Black Sky or Airbus Defense and Space). Improvements will also occur in unmanned aerial vehicles and phenocams with increasing multispectral, hyperspectral, and thermal imaging, and LiDAR. In addition, deep learning and computer vision methods, applied to high resolution imagery, will open the possibility of detecting and monitoring plant and animal populations with unprecedented efficiency (Guirado et al., 2017).

A large amount of high-resolution data is now available and shared through a revolution of emerging open-source and user-friendly platforms with increasing processing capabilities (e.g., Google Earth Engine, Remap and AppEEARS; Kwok, 2018). We are witnessing an exponential integration of remote sensing information with data from many other disciplines (e.g., social media, citizen science, molecular information; Kissling et al., 2018), through exceptional computational algorithms and processing approaches (Leitão and Santos, 2019), such as data-fusion techniques and artificial intelligence (Guirado et al., 2017; Safonova et al., 2019). These developments will further widen the horizon for invasion science's remote sensing revolution.

AUTHOR CONTRIBUTIONS

AV identified the opinion subject, contributed to the content of the paper, coordinated the contributions of the other co-authors, and drafted the manuscript. DA-S, JV, and JH contributed to the design and implementation of the arguments underlying this opinion and to the development and writing of the ideas presented in this manuscript.

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