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Review

On the edge: The use of infrared thermography in monitoring responses of intertidal organisms to heat stress

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ABSTRACT

Monitoring changes in the environment and the corresponding effects on biological systems still represents a major challenge in many marine and terrestrial ecological studies. Infrared thermography (IRT), and its application within the marine environment, represents an effective non-invasive tool for measuring the temperatures of organisms and their surrounding environment *in situ*. The use of IRT within the intertidal zone is particularly useful since habitat and organismal temperatures are highly variable across both fine spatial and temporal scales. We review the growing number of intertidal studies that utilise IRT to investigate the role of small-scale temperature variability in contributing to various demographic and ecological processes. In particular, we introduce two indicators of the thermal quality of intertidal habitats that can be readily used by ecologists but also management and conservation policy makers to assess the suitability of a given habitat for a range of species under actual and predicted climatic conditions. We also outline a range of potential applications involving IRT that have yet to be explored for monitoring coastal environments. These include combining photogrammetry, unmanned aerial vehicles and IRT to large-scale three-dimensional thermal maps of intertidal habitats. We also suggest ways in which this technology could facilitate environmental management objectives in a warming world, such as the identification and quantification of thermal refugia across various spatial and temporal scales. We affirm with previous studies that such thermal refugia are vital for the adaptation of intertidal communities to climate change and that IRT could facilitate more effective management and conservation of these areas. The IRT applications outlined in this review are by no means exhaustive or limited to rocky intertidal environments. We envision that IRT will become increasingly popular as environmental management agencies become increasingly concerned about global climate change and how to combat its negative consequences on ecosystems.

1. Introduction

1.1. Monitoring ecological responses to climate change

As biological systems and ecosystem processes continue to change in response to increasing temperatures associated with climate change it is paramount that environmental managers and conversation strategies incorporate the necessary tools for monitoring and predicting these future changes. In the past, this has largely been achieved by utilising long-term meteorological data but such records are usually somewhat removed from the actual conditions experienced by target organisms within their specific microhabitats (Lathlean et al., 2011; Stobart et al., 2016). Indeed, many recent marine and terrestrial studies have demonstrated that small-scale temperature variability can be extremely heterogeneous and that this can have significant implications for the persistence and viability of species and populations in a warming world (Woods et al., 2015).

Infrared thermography (IRT) serves as a powerful non-invasive tool for rapidly detecting and measuring fine-scale variations in temperatures. Such measurements have proven to be particularly useful in measuring body temperatures of small ectothermic organisms (e.g. Chapperon and Seuront 2011a) as well as identifying and characterising small-scale thermal refugia utilised by such organisms during extreme heat events (e.g. Lathlean 2014). Due to the rapid attenuation of infrared radiation underwater, ecological studies that use IRT have largely been undertaken on terrestrial systems, whilst being limited to surfacing animals in aquatic ecosystems. In recent years, however, IRT has been used to investigate the thermal ecology and physiology of

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intertidal organisms, those species which live at the land-sea interface and are intermittently exposed by the receding tide.

Intertidal ecosystems are home to some of the world's most biologically diverse and productive communities but are particularly vulnerable to climate change because (i) many organisms in these ecosystems are already living at or close to their upper thermal limits (Stillman and Somero 2000; Somero 2010); (ii) rising sea levels and greater extreme temperatures are limiting the amount of suitable habitat available for these organisms; and (iii) anthropogenic activities and disturbances are generally the greatest along coasts. Therefore, the application of IRT within the intertidal zone has been quite crucial and is fast becoming widely used by marine ecologists and environmental managers alike (Lathlean and Seuront, 2014). This review outlines some the most common applications of IRT in the marine environment to date, focusing on several case studies undertaken across contrasting intertidal habitats, including rocky shores, mangrove forests and saltmarsh communities. It also discusses best practices and common pitfalls associated with using IRT within intertidal habitats, whilst identifying fruitful areas of future research and applications within aquaculture, resource management and conservation. In particular, we introduce two indicators of the thermal quality of intertidal habitats that can be readily used by ecologists but also management and conservation policy makers to assess the suitability of a given habitat for a range of species under actual and predicted climatic conditions.

1.2. Brief history of infrared thermography

The detection and quantification of infrared radiation has become one of the most diverse and important scientific applications since it was first discovered by Sir William Herschel in 1800 through his classic prism experiment to refract natural light. Initially used by astronomers to detect distant planets and hidden stars, infrared detection and imaging were quickly utilised for military purposes including target acquisition, night-vision and guided missile systems. Many commercial applications quickly followed as the relative cost and sophistication of infrared imaging technology became increasingly affordable and available. Such commercial uses to date include: surveillance, law enforcement, medical diagnosis, satellite imagery, electrical engineering, construction, pest control and veterinary science, just to name a few.

Since the first Earth Observation Satellite was launched in 1959, meteorologists and oceanographers have relied heavily on large-scale infrared images to monitor and forecast regional weather patterns and climate variability. Today, satellite-measured reflectances in the red, near infrared and infrared band of the electromagnetic spectrum are used by terrestrial ecologists to map large scale changes in vegetation cover (Vorovencii et al., 2013), primary productivity (Nouvellon et al., 2000) and photosynthetic efficiencies of entire ecosystems (Coops et al., 1998). Similarly, oceanographers utilise satellite images of sea-surface temperatures to produce detailed maps and models of oceanographic currents and surface properties. However, non-satellite-derived applications of infrared thermography (hereafter IRT) taken at small spatial scales have only come about in the last 20 years or so. Within the ecological literature, IRT was introduced in the late 1980s as a non-invasive tool for measuring body temperatures of lizards (Jones and Avery 1989). Since then IRT has become increasingly portable and sophisticated being used extensively for nocturnal surveys of bats, owls and rodents (McCafferty et al., 1998; Pregowski et al., 2004; Hristov et al., 2008; McCafferty 2013) and for tracking and quantifying the abundances of large mammals such as deer and polar bears (York et al., 2004; Butler et al., 2006). The most recent high-resolution infrared cameras have even been used to map fine-scale thermal properties of individual leaves and the implications on the thermoregulation of herbivorous arthropods (Caillon et al., 2014).

Whilst IRT is an effective method for capturing thermal variability on land, it is considerably less effective in the ocean, where infrared waves are rapidly attenuated by seawater. Many deep-sea fish are capable of detecting near infrared radiation (NIR) to capture prey and scientists have utilised NIR lights to observe the natural behaviour of deep-sea fish but such applications cannot be used to estimate temperatures of objects under water. Species living within the intertidal zone, however, are intermittently exposed to the atmosphere up to 12 h each day, which provide a unique opportunity to apply IRT to marine organisms (Lathlean and Seuront 2014).

2. Intertidal ecosystems – Bellwethers of climate change

2.1. Importance of intertidal systems

Apart from having a long history of ecological research, particularly rocky shores, intertidal systems constitute an important interface between the land and sea, and is characterised by steep environmental gradients. They also represent an important biome that is integral for the proper ecological functioning and cycling of nutrients within both terrestrial and marine environments. Although generally restricted to a 2–3 m band of rocky substrata around the edge of the ocean, rocky shores represent one of the most diverse and productive ecosystems on the planet. Despite the longstanding need to quantify the fluxes of carbon from continental margins to open ocean basins (Capone et al., 2006; Falkowski et al., 1998), scarce attention has been given to intertidal zones as a carbon source (Liu et al., 2000). Carbon fluxes and exchanges between the countless littoral shallow-water ecosystems and the open coastal zone have yet to be included in the global calculation of the carbon budget. Intertidal ecosystems have, therefore, been put forward as the ‘missing carbon sink’, characterised as a widespread network of ‘small’ sinks that capture an estimate of 1.8 ± 0.5 PgC y^{-1} (Guarini et al., 2008). Understanding the structure and function of intertidal habitats and their responses to future climate change is, therefore, of particular relevance to environmental managers and conservation programs that are concerned with sustaining the ecological and economic subsidies that these systems provide. For example, the worldwide value of ecosystem goods (e.g. food and raw materials) and services (e.g. disturbance regulation and nutrient cycling) provided by habitats from the intertidal zone out to the continental shelf break are estimated be over US$14 trillion per year or ~43% of the global total (Costanza et al., 1997). Yet it is often these intertidal environments that are most at risk of anthropogenic disturbances such as land-clearing and over-exploitation. Furthermore, with many intertidal organisms already living at or close to their thermal limits intertidal communities may act as a sensitive bellwether for global climate change (Somero 2010; Somero, 2010Somero 2010; Denny and Harley 2006, Helmuth 2006).

2.2. Types of intertidal habitats

Intertidal habitats are as diverse as the biological communities they support and are generally categorised based on the type of substratum (hard or soft) and level of exposure (estuary or coast). Intertidal habitats with hard rocky substrata are commonly found in more exposed environments towards the entrance of estuaries and along the open coastline. These are collectively referred to as ‘rocky shores’ (Fig. 1a) and are usually topographically complex with numerous microhabitats including rock pools, crevices, boulders and emergent platforms. Along with a steep thermal gradient these microhabitats produce substrata with highly heterogeneous temperatures during aerial exposure, which can be captured effectively using IRT (see Fig. 2). Intertidal habitats with soft-sedimentary substrata can be found both within estuaries (e.g. mangrove forests; Fig. 1b; or coastal saltmarshes; Fig. 1d) or along open coasts such as sandy beaches (Fig. 1c). Sandy beaches are less topographically variable than rocky shores resulting in lower thermal heterogeneity. However, stranded wrack (i.e. seaweed) and other decomposing matter along the shoreline may increase thermal heterogeneity and produce microhabitats that would otherwise be non-existent (Fig. 1e). Soft sedimentary intertidal