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SPECIAL ISSUE: CONCEPTS AND CONTROVERSIES IN TIDAL MARSH ECOLOGY REVISITED

Novel Applications of Technology for Advancing Tidal Marsh Ecology

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Abstract

Over the last 20 years, innovations have led to the development of exciting new technologies and novel applications of established technologies, collectively increasing the scale, scope, and quality of research possible in tidal marsh systems. Thus, ecological research on marshes is being revolutionized, in the same way as ecological research more generally, by the availability of new tools and analytical techniques. This perspective highlights current and potential applications of novel research technologies for marsh ecology. These are summarized under several themes: (1.) imagery — sophisticated imaging sensors mounted on satellites, drones, and underwater vehicles; (2.) animal tracking — acoustic telemetry, passive integrated transponder (PIT) tags, and satellite tracking, and (3.) biotracers — investigation of energy pathways and food web structure using chemical tracers such as compound-specific stable isotopes, isotope addition experiments, contaminant analysis, and eDNA. While the adoption of these technological advances has greatly enhanced our ability to examine contemporary questions in tidal marsh ecology, these applications also create significant challenges with the accessibility, processing, and synthesis of the large amounts of data generated. Implementation of open science practices has allowed for greater access to data. Newly available machine learning algorithms have been widely applied to resolve the challenge of detecting patterns in massive environmental datasets. The potential integration on digital platforms of multiple, large data streams measuring physical and biological components of tidal marsh ecosystems is an opportunity to advance science support for management responses needed in a rapidly changing coastal landscape.

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Introduction

Tidal marshes are dynamic and interconnected habitat mosaics embedded in coastal and estuarine environments. The structure of tidal marshes depends on their physical and environmental characteristics, including foundation species, geomorphology, tidal regime, and sediment and water supply and sources (Ziegler et al. 2021). The function of tidal marshes depends on their capacity to support individual organisms and their population and community dynamics. The structure and function of marshes is influenced by local (e.g., pollution), regional (e.g., catchment alteration), and global (e.g., sea level rise) drivers, both natural and anthropogenic.

Scientists have examined tidal marsh structure and function at all levels over the past 60 years (Taylor et al. this issue; Weinstein and Kreeger 2000). Core pillars of tidal marsh research include: biogeochemical processes; nutrient and energy fluxes; sources, patterns, and fates of tidal marsh production in aquatic food webs; habitat values in terms of provision of food and refuge for a wide variety of species; and restoration design and monitoring. Over the last 20 years, innovations have led to the development of exciting new technologies and novel applications of established technologies, collectively increasing the potential scale, scope, and quality of tidal marsh research. Examples range from robust, portable instruments capable of recording in situ observations on stationary or mobile instrument platforms (both aerial and underwater) to computer systems with increased analytical capacity. Coupled with decreasing size and cost, novel applications of technologies are becoming more accessible. In addition, a variety of historic and current sources of research material are now available in public databases, to examine spatial and temporal variability in these systems.

Here, we highlight recent technological advances and novel applications in tidal marsh ecology research. Specifically, we examine how innovations advance understanding of the structure and function of tidal marshes (Gilby et al. 2020), geographic variation in these patterns (Ziegler et al. 2021), the influence of climate change (Colombano et al. 2021), and implications for restoration of these systems (Waltham et al. 2021). We describe key areas of development, introducing relevant technologies and discussing their application in the investigation of contemporary issues in tidal marsh ecology. We conclude by discussing open science practices and exploring the analytical techniques developed for processing and synthesizing the large amounts of data generated by these new technologies.

Technological Advances

Technological advances with relevance to the study of tidal marshes, particularly in relation to marsh support of fisheries (Baker et al. 2020), have been introduced or developed over the past two decades (Table 1), with advances in imagery, animal tracking, and biotracers being especially important. Each of these categories includes established technology that has existed for some time, but relatively recent advances in these technologies have improved the scope of their application, and the quality of data or inference possible from the technology. Importantly, this has coincided with reduced costs associated with acquiring and utilizing these technologies, making them accessible to a broader spectrum of researchers, and their incorporation at broader scales.

Imagery Collection of optical or refractive light imagery (both remote and in situ) and acoustic imagery is increasingly used to address diverse questions regarding structure, function, and longitudinal changes in tidal marsh ecosystems. Imaging sensors (e.g., thermal and hyper-spectral) are becoming increasingly sophisticated, mounted onto platforms ranging from satellite to submersible, and supporting an expanding array of applications in tidal marsh ecology. Drones are becoming common tools in tidal marsh ecology (Abeysinghe et al. 2019; Kelaher et al. 2019), because they allow researchers to acquire aerial imagery using simple, affordable, and easily repeatable methods. Drones are able to collect imagery at high resolutions (e.g., centimeters); cameras onboard drones can operate at much lower altitudes and achieve higher spatial resolutions than those onboard conventional aircraft and satellites (Colomina and Molina 2014; Pajares 2015). For example, using high-resolution (e.g., 2.3 cm) unmanned aerial systems structure-from-motion (UAS-SfM) photogrammetry methods, Kalacska et al. (2017) mapped marsh features such as distributions of plant communities and hydrological connectivity among ponds varying in elevation by centimeters or less. Other examples include monitoring mudflat sediment morphodynamics and small-scale sedimentary structures in tidal marshes (Jaud et al. 2016) and identifying and mapping habitats and fish behaviors (Ventura et al. 2016; Colombano et al. 2020a) using high-resolution, geo-rectified photomosaic in red, blue, green (RGB) and normalized difference vegetation index (NDVI) imagery (Matso et al. 2019).

Hyper- and multi-spectral imaging spectrometers enable spectral discrimination of tidal marsh habitat types (e.g., foundational species assemblages), among other applications. Over the last two decades, improvement of satellite spatial resolution, the emergence of drones, and reduced costs of

Table 1 Technological advances used in tidal marsh ecology research related to imagery, animal tracking, biotracers, and environmental sensors. Relevant references related to each technology are provided

Category	Technology	Key advancements and application in tidal marshes	Relevant references
Imagery	High-resolution aerial imagery	● High-resolution imagery of habitats and hydrological features collected at low altitudes that can be used to identify plants and assess elevation - Unmanned aerial systems (UAS) are capable of inexpensively collecting high-resolution imagery at regular intervals - Improved satellite technologies now capable of acquiring imagery at resolutions < 5 m - Mapping below-water tidal marsh habitats (e.g., WorldView satellites)	Colomina and Molina (2014); Pajares (2015); Jaud et al. (2016); Ventura et al. (2016); Kalacska et al. (2017); Abeysinghe et al. (2019); Roegner et al. (2019); Colombano et al. (2020a); Dohner et al. (2020)
	Hyper- and multi-spectral imagery	● Object-specific reflectance patterns, or spectral signatures, used to discriminate object types (e.g., plant species mixtures) in the spectral imagery - Hyper- and multi-spectral imagers now collected at high resolutions necessary for surveying tidal marsh habitats - Normalized difference vegetation index (NDVI) imagery for habitat assessments - Long-term spectral dataset archives to track longitudinal change in plant assemblages	Rapinel et al. (2014); Santos et al. (2018); Lopes et al. (2019); Matso et al. (2019)
	Underwater video imagery	● Low-cost camera arrays with automated identification and counting of fish where water clarity allows - Faunal surveys at greater spatial and temporal scales with minimal sampling effort	Konovalov et al. (2019); Ditria et al. (2020a, 2020b)
	Acoustic imagery	● Dual-frequency IDentification SONar (DIDSON) and Adaptive Resolution Imaging Sonar (ARIS) acoustic cameras - Near-video-quality imaging in zero-visibility environments, such as tidal marshes - Species identification supporting quantitative surveys of large fishes	Boswell et al. (2008); Becker et al. (2011); Martignac et al. (2015); Boswell et al. (2019); Lankowicz et al. (2020); Bennett et al. (2020)
Animal tracking	Acoustic telemetry	● Animal-mounted ultrasonic transmitters for monitoring animal behavior, habitat use, and connectivity, along with species interactions within tidal marshes - Miniaturization allows tracking of small-bodied fishes and crustaceans - Positioning systems improve qualification of micro-habitat selectivity within tidal marshes - Sensor transmitters (e.g., temp, depth, and acceleration) reveal relationships between tidal marsh environmental metrics and animal behavior - Mobile receivers (e.g., gliders and business card tags) increase opportunities to track animals at greater spatial scales - Collaborative telemetry networks greatly enhance spatial and temporal resolution of detection data	Taylor and Ko (2011); Grothues et al. (2012); Dance and Rooker (2015); Haulsee et al. (2015); Hussey et al. (2015); Stehfest et al. (2015); Berejikian et al. (2016); Cooke et al. (2016); Whitney et al. (2016); Moulton et al. (2017); Taylor et al. (2017); Griffin et al. (2018); Stevenson et al. (2019)
	Passive integrated transponder (PIT) systems	● Animal-mounted PIT tags for tracking of animal movement, behavior, and habitat selectivity in tidal marshes - PIT detection arrays adapted for saline environments have expanded opportunities for tracking animals in tidal marsh systems, particularly small juveniles - Supports "mark-recapture" studies in tidal marshes, to estimate animal mortality	Connolly (2010); Hering et al. (2010); Rudershausen et al. (2014); Kimball et al. (2017); Garwood et al. (2019); Colombano et al. (2020b); Kimball and Mace III (2020)
	Satellite tracking	● Animal-mounted satellite tags allow tracking of tidal marsh-associated species over unrestricted spatial scales - Miniaturization allows tracking movements of smaller-bodied species	Beauchamp et al. (2018)

Table 1 (continued)

Category	Technology	Key advancements and application in tidal marshes	Relevant references
		- Sensor-equipped tags also measure variables to inform potential drivers of movement	
Biotracers	Bulk tissue and compound-specific stable isotopes	● $\delta^{15}N$, $\delta^{13}C$, $\delta^{34}S$, $\delta^{18}O$, and $\delta^{2}H$ isotopes provide space- and time-integrated information on trophic interactions, including trophic level, carbon source, niche width, trophic position, connectivity, and habitat use - Compound-specific isotope ratios allow measurement of microbial components of marsh food webs and historical sedimentary processes	Connolly et al. (2004); Bouillon et al. (2011); Galvan et al. (2011); Layman et al. (2012); Baker et al. (2013); Middelburg (2014); Nelson et al. (2015); Freimuth et al. (2019); Johnson et al. (2019); Lesser et al. (2020); Harris et al. (2020)
	Pollutants and trace metals	● Trace metals, and other organic and inorganic contaminants, provide tracing of energy flow and connectivity in marsh systems - Flux measurements to derive filtration rates in marshes	Chen et al. (2016); Fonseca et al. (2019)
	eDNA metabarcoding	● Environmental DNA to identify patterns of species presence, abundance, and diversity within tidal marshes	Cristescu (2014); Berry et al. (2015); Ruppert et al. (2019); Foster et al. (2020); Zou et al. (2020)
Environmental sensors	Water level recorders	● Digital, compact, and self-contained low-cost pressure transducers log data remotely over extended periods - Collection of long-term, low-frequency inundation data throughout tidal marshes - Technology is often self-customizable to suit user needs - High-frequency (> 1 Hz) water level recorders allow wave spectra to be determined and thus allow estimation of wave attenuation, erosion, and sediment transport - Array of recorders allows direct measurement of wave attenuation across a marsh	Raposa et al. (2017); Temple et al. (2020)
	Acoustic velocimeters (ADV) and acoustic Doppler current profilers (ADCP)	● High frequency, 3D logging of flow velocity and micro-current properties - Fixed-position unit measures flows through marsh systems over time - Mobile (boat or unmanned surface vehicles) to cover broader spatial scales and micro-current patterns - Monitoring of cross-channel flows to evaluate restoration against objectives - Extension of ADCP and optical backscatter sensors to monitor suspended sediment concentrations	Coulombier et al. (2012); Whipple et al. (2018)
	Water quality loggers	● Single or multi-parameter loggers support monitoring of hydrography and habitat quality throughout marsh systems - Larger memory and battery capacity, low cost, and small size, for remote monitoring of temperature, DO, pH, conductivity, chl-a, and turbidity across broad scales - Wireless data transmission can support real-time remote monitoring systems (RTRM)	Glasgow et al. (2004)

multi- and hyper-spectral sensors have increased the scope for application of spectral imaging to advance study of tidal marshes. Multi-spectral satellite imagery can now be acquired at resolutions < 5 m, enabling examination of tidal marsh systems at much finer scales and supporting longitudinal analyses of change over extended periods (Lopes et al. 2019). Deployment of satellites with spectral bands specialized for high-resolution coverage of coastal environments (e.g., WorldView-2 and WorldView-3) now allows mapping of both land and below-water tidal marsh habitats (Rapinel et al. 2014; Santos et al. 2018). Incorporation of spectral sensors with drone technology also supports collection of high-resolution hyper-spectral data that is important in many different contexts (e.g., time series to evaluate habitat restoration within tidal marshes; Roegner et al. 2019). These advances support increases in the quality, volume, and diversity of applications of spectral imagery in the study of tidal marshes, in particular, measuring the geomorphological and floral impacts of the myriad of stressors that will perturb these systems into the future (Colombano et al. 2021; Gilby et al. 2020), as well as the success of restoration efforts (Waltham et al. 2021).

Technological advances in video cameras, sensors, battery life, and data storage (Mallet and Pelletier 2014) have led to enhanced opportunities for application of both optical and acoustic underwater imaging to study tidal marshes. Underwater video has been used to examine the abundance and behavior of fauna as well as abiotic characteristics such as sediment properties, flocculation rates, and geomorphological processes (Morris et al. 2007). Despite these being important metrics in the study of tidal marshes, there have been comparatively few applications of this technology in this habitat; however, this is expanding (e.g., Baker and Waltham 2020; Jones et al. 2020). Where turbidity levels in tidal marsh habitats preclude the use of traditional underwater video, acoustic imaging sonars (e.g., DIDSON, ARIS) can "see" with sound in zero visibility conditions, making it possible to track motile organisms and delineate underwater structures (e.g., Boswell et al. 2008). Acoustic imaging sonars use sound to create high-resolution continuous video-like imagery and can operate at various temporal and spatial scales both day and night, with minimal or no disturbance to animals or habitats, and much reduced effort (e.g., Becker et al. 2011; Boswell et al. 2019). Acoustic imagery allows for observation of underwater habitats as well as the size, abundance, and behavior of animals (although species identification is limited) and thus provides opportunities to develop and test hypotheses regarding factors controlling habitat use, bioturbation, migration, trophic interaction, and other processes that cannot be addressed with traditional sampling approaches or experiments (Lankowicz et al. 2020; Bennett et al. 2020).

Animal Tracking Identifying spatial and temporal movement patterns of animals has refined our understanding of the physiology, behavior, and ecology of species in tidal marsh systems, and the value of the habitats they utilize (Furey et al. 2013; Drymon et al. 2014). In addition, the use of newly developed tracking tools and technologies has greatly enhanced our ability to observe animal movement and behavior as well as advance our understanding of animal-environment interactions (Tibbetts 2017; Nguyen et al. 2019). Acoustic telemetry has become one of the most widely used technologies for investigating aquatic animal movement. Significant advances in the last 20 years have resulted in unprecedented insights into the ecology and biology of tidal marsh species (Hussey et al. 2015; Taylor et al. 2017). Miniaturization of acoustic transmitters has enabled researchers to track smaller individuals, allowing application to a wider range of species and life stages (Taylor and Ko 2011; Stevenson et al. 2019). Improvements in acoustic receiver and detection processing software have made it easy to triangulate precise animal locations and allowed for observations of fine-scale habitat preferences and species interactions (Dance and Rooker 2015; Moulton et al. 2017). The microhabitat-level understanding achieved using this fine-scale tracking includes details such as shoreline slope preferences (Furey et al. 2013) and substrate preferences (Moulton et al. 2017) that are critical in determining best practices for tidal marsh conservation and restoration. Transmitters with built in temperature, depth, and acceleration sensors have been used to examine animal physiology and behavior (Stehfest et al. 2015; Cooke et al. 2016), with accelerometer transmitters particularly useful in examining post-fishing release mortality (Whitney et al. 2016). Increased use of mobile receivers attached to platforms of opportunity such as autonomous vehicles (Grothues et al. 2012; Haulsee et al. 2015) has increased opportunities to track animals at greater spatial scales (e.g., in multiple estuaries along an entire regional coastline). Sampling approaches incorporating the use of peer-to-peer telemetry technologies (e.g., "business card" tags and animal-borne mobile transceivers) will offer new opportunities for characterizing community level interactions among species and individuals within and among tidal marsh systems (Berejikian et al. 2016).

Advances in passive integrated transponder (PIT) technology have enabled researchers to more effectively track fine-scale movement and habitat use of animals in tidal marsh habitats. PIT technology has been used for more than 25 years in freshwater systems but has only relatively recently been used to track individual fish movement in saline tidal marshes (e.g., Rudershausen et al. 2014; Garwood et al. 2019; Colombano et al. 2020b). The development of autonomous antenna array systems has enabled researchers to passively detect tagged individuals, eliminating intensive field collections and significantly increasing rates of "recapture" (Connolly 2010). However, to date, PIT tags have been used to examine the behavior of only a small percentage of motile species in marsh systems (Kimball et al. 2017; Kimball and Mace 2020). Whereas the utility of autonomous antennas in estuarine environments has proven useful, application of this sampling approach has been restricted to narrower creek channels or similar choke points in managed marshes (e.g., water control structures; Kimball et al. 2017) due to limitations in antenna coil capacity. Future research identifying species-specific PIT-tagging possibilities (e.g., Kimball and Mace 2020) and techniques to increase detection efficiency with PIT antenna arrays (sensu Hering et al. 2010) will significantly improve the application of this tool in tidal marsh ecology.

Modern tracking applications such as acoustic telemetry and PIT technology are likely to be applied henceforth to a much wider range of species. In combination with potential satellite tracking of larger-scale animal movements (Beauchamp et al. 2018), the expected surge in tracking data should reveal key interactions between species and their microhabitats that have remained indiscernible until now.

Biotracers The use of biochemical tracer techniques has grown steadily during the past two decades, revealing predator-prey interactions, trophic structure, and energy pathways in tidal marshes. Common biotracers include bulk tissue and compound-specific stable isotopes, persistent bioaccumulative pollutants and trace metals, and DNA techniques (Layman et al. 2012; Middelburg 2014; Cristescu 2014). These tracers have several advantages over the direct empirical assessment of energy flow (e.g., via stomach content or scat and spew analysis) since they are assimilated through multiple pathways and integrated over long timescales (weeks to years, depending on the tissue analyzed), providing time- and space-integrated information on trophic interactions (Bouillon et al. 2011; Layman et al. 2012). Stable isotopes of nitrogen (N), carbon (C), hydrogen (^{2}H:^{1}H), oxygen (^{18}O:^{16}O), and sulfur (^{34}S:^{32}S) (Peterson and Fry 1987; Connolly et al. 2004) are increasingly being used to quantify carbon source contributions, dietary composition, niche width, and trophic position (Bouillon et al. 2011; Nelson et al. 2015; Lesser et al. 2020; Harris et al. 2020).

Additional taxonomic and temporal resolution (due to faster turnover rates) in trophic relationships and the contribution of basal resources can be gained through the application of isotope addition experiments and compound-specific stable isotope analysis. Experimental addition of artificially enriched isotopes can provide very precise measures of food web pathways. In marshes, for example, the addition of dual C/N enriched isotopes has been used to separate contributions to food webs from in situ marsh plants and phytoplankton (Galvan et al. 2011). Compound-specific analysis can more precisely track assimilation by animals of particular food sources. For example, Johnson et al. (2019) used compound-specific amino acid isotopes to report equal contributions of terrestrial and aquatic carbon sources supporting a marsh consumer (seaside sparrows), with greater precision than was possible using bulk tissue analysis. Further, compound-specific isotope analysis of lipids enables improved definition of the microbial compartment of food webs, a critical need in determining the role of detritus in marsh food webs (Middelburg 2014), and potentially also of historical sedimentary processes in marshes (Freimuth et al. 2019). In addition, coastal marshes are renowned sinks of pollutants and trace metals. Organic forms of compounds such as mercury, a widespread coastal pollutant, have a high biomagnification potential and in combination with stable isotopes have been used in estuaries to examine the relationship between pollutant concentration and consumer foraging mode (Chen et al. 2016), and spatial variation in food web structure in relation to sources of pollution (Fonseca et al. 2019).

DNA metabarcoding is another emerging technology used to better describe diversity in marsh communities (Cristescu 2014). The approach relies on the sequence of standardized DNA fragments to identify individual species using known DNA barcode libraries with high-throughput sequencing to identify entire assemblages (Ruppert et al. 2019). In coastal systems, the technique has been applied to study both present and past marsh biodiversity (Foster et al. 2020; Zou et al. 2020), and trophic diversity (Berry et al. 2015), by identifying species from traces of DNA present in environmental and diet samples. In the future, continued improvements in both analytical technologies and sophisticated statistical approaches will broaden the scope of application of biomarkers to tackle a variety of questions in marsh ecology.

Data Processing, Synthesis, and Accessibility

While the approaches outlined above greatly increase the scope and scale of research in tidal marshes, their application creates several challenges for the processing, storage, analysis, and sharing of the resulting large datasets. In this section, we highlight how data science practices and philosophies might allow researchers to more efficiently study tidal marshes at finer resolutions, over longer time periods, and at greater spatial scales.

An Open Science Framework “Open science” describes a framework for transparency throughout the research process (Fecher and Friesike 2014), with an emphasis on “data stewardship” rather than “data ownership” (Hampton et al. 2015). Significant effort has been made toward developing open science data formats and infrastructure such as data repositories, computational services, and open-access tools (e.g., Google Earth Engine, QGIS, and R software environment) which has resulted in integrated frameworks that promote data literacy, transparency, collaboration, visibility, and, most importantly, reproducibility. An open science framework for tidal marsh research can improve our chances of quantifying local and global changes due to cumulative stressors. Big data, data sharing, and the computational frameworks possible under the open science philosophy provide novel opportunities for collecting and analyzing data across the temporal and spatial scales that are necessary to appreciate the implications of ecological changes. As an example, climate change and sea level rise are two of the most significant stressors likely to impact tidal marshes into the future (Colombano et al. 2021). These are most likely to initially manifest in changes to the diversity and distribution of foundational species assemblages, both within marsh systems, and across latitudinal scales, and these changes will foreshadow downstream effects on tidal marsh function (Baker et al. 2020; Gilby et al. 2020). Compilation, sharing, and analysis of remote sensing data will provide an invaluable resource for assessing longitudinal trends to develop and inform conservation measures.

Machine Learning Analysis of large datasets is commonly hampered by the manual steps required during data processing workflows (e.g., species identification in videos; Ditria et al. 2020a). Machine learning, a subset of artificial intelligence, is revolutionizing data analysis in ecology and is increasingly common in investigating tidal marsh ecology (Christin et al. 2019). There is large potential for pattern recognition (e.g., image analysis; Ditria et al. 2020b), predicting spatiotemporal variability in ecological processes, and data exploration to infer system processes and develop new hypotheses. For example, passive data recorders such as time-lapse and underwater cameras can collect large amounts of imagery on species distributions, but manual processing hampers data synthesis. The combination of machine learning with computer vision overcomes this processing bottleneck, in both land cover and underwater imagery (Lopez-Marcano et al. 2021), providing a potential step change in the magnitude of data processing.

Tidal marsh ecosystems are notoriously dynamic and complex, leading to difficulties in accurately predicting spatiotemporal variability that occurs. Machine learning methods are valuable for modeling non-linear, highly dimensional data while accounting for complex interactions (Olden et al. 2008). Banerjee et al. (2019) used artificial neural networks, biologically inspired multi-layered computational networks consisting of interconnected units similar to neurons in the human brain, to model dissolved oxygen (DO) and zooplankton abundance using a large number of environmental variables. The artificial neural network models regularly outperformed regression models in predicting DO and zooplankton abundance (Banerjee et al. 2019). Machine learning approaches are especially useful when synthesizing related data from multiple sources and can effectively handle missing data (Olden et al. 2008). These approaches show great promise in tidal marsh ecosystems to analyze spatiotemporal variability in ecological processes.

Machine learning is frequently being applied as a data exploration tool for identifying relationships among variables in large ecological datasets. Data mining techniques such as tree-based methods, support vector machines, and Bayesian inference are more effective at uncovering relationships within large complex datasets than traditional statistical modeling procedures (Hochachka et al. 2007; Teichert et al. 2016). For example, machine learning has been used to predict how biodiversity will shift with climate change (Baltensperger and Huettmann 2015), which is an emerging theme in tidal marsh ecology research (Colombano et al. 2021). Future applications of machine learning can improve our understanding of tidal marsh ecosystems by analyzing vast amounts of data collected through traditional research activities and generated by our highly networked society (e.g., Becken et al. 2017).

Conclusions

The technological advances highlighted above will continue to further tidal marsh ecology research endeavors. While the power of individual approaches is obvious, it is the synergies of these approaches that have significant potential for sparking transformative research and supporting ecosystem-based management of tidal marshes. For example, combining biological knowledge of animal abundance and behavior garnered through underwater imagery (e.g., Boswell et al. 2019; Bennett et al. 2020) or tracking data (e.g., Dance and Rooker 2015; Colombano et al. 2020b) with continuous abiotic water quality and water level observations (e.g., Glasgow et al. 2004; Raposa et al. 2017; Temple et al. 2020) collected at coincident spatial and temporal scales can greatly improve our understanding of tidal marsh ecosystems. In addition, characterization of the physical and environmental aspects of tidal marsh habitats afforded through advances in capability and affordability of sensors for measuring flow velocities, sediment concentrations, and wave energy (e.g., Coulombier et al. 2012; Whipple et al. 2018; Temple et al. 2020) and high-resolution aerial and underwater imagery (e.g., Abeysinghe et al. 2019; Dohner et al. 2020) provides fine-scale temporal and spatial habitat details that can facilitate more in-depth interpretation of their function for organisms. Further, while comprehensive assessments of the spatial ecology of fishes, mammals, reptiles, and invertebrates are fundamental to understanding the function of tidal marshes, collecting data at larger, ecologically relevant scales for some species can be difficult. The development of collaborative networks, such as those established for acoustic telemetry, can expand research capacities to regional or global scales by allowing for tracking animals among multiple tidal marsh systems, while also maximizing the value of limited resources (e.g., transmitters, hydrophones, and researcher time) and strengthening the value of the data collected (Griffin et al. 2018). Further development of advanced computing technologies, such as deep learning algorithms, will help minimize the challenges associated with processing these large volumes of data and integrating this knowledge into management initiatives (Ditria et al. 2020a; Konovalov et al. 2019).

Many of these novel research techniques still need to be used in conjunction with more traditional methods, as newer methods often require "ground truthing" against "conventional data." For example, remotely sensed vegetation mapping needs validating with field surveys, and automated fish monitoring using sonar or eDNA sampling requires direct capture of fish for confirmation of accuracy (e.g., Martignac et al. 2015). Conversely, this will also assist in validating interpretations of data collected using conventional methods. Furthermore, long-term estuarine research programs which continue using traditional methods (e.g., state or federal agency surveys) may be greatly enhanced by incorporating novel technologies into sampling protocols. Monitoring of fish and crustacean assemblages in tidal marshes is a primary means of understanding tidal marsh function; however, traditional approaches inevitably lead to mortality and have inherent biases when used to assess abundance (Rozas and Minello 1997; Connolly 1999). In addition to the technological advances discussed above, the development and novel application of direct capture techniques such as electrofishing units capable of functioning in saline tidal marsh waters can provide an alternative, less biased approach for monitoring these organisms and may warrant more widespread use (Warry et al. 2013; Lieschke et al. 2019).

Tidal marsh ecosystems are likely to continue facing major impacts from human activities, threatening the provision of services that coastal communities rely on (Colombano et al. 2021). These changes will need considered, active management to optimize outcomes for marsh protection and restoration (Waltham et al. 2021). The technological advances highlighted in this perspective can play an important role in helping to provide science support for management. Integrated digital platforms capable of incorporating and analyzing multiple, massive data streams are revolutionizing operating practices in many industries. Adapting the exciting potential of these platforms and integrating multiple data streams measuring physical and biological components of tidal marsh ecosystems will create unprecedented opportunity to match science advances with the need for management and conservation in a rapidly changing coastal landscape.

Declarations

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