Greenhouse gas flux measurements with the static chamber method in tidal environments – a review

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Contents

1. Introduction 3
2. Static chamber method – collars or no collars 5
3. Collars in tidal environments 7
4. General considerations 9
5. Summary 11
6. References 13
Appendix 1 – Overview of reviewed papers 19

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1. Introduction

Vegetated costal ecosystems provide a globally significant long-term carbon store with greater carbon burial rates per unit area than terrestrial ecosystems (Mcleod et al., 2011). These tidal ecosystems achieve this through a combination of trapping and burying allochthonous (external) carbon and in-situ (autochthonous) carbon. The latter occurs mainly through CO_2 fixation as part of photosynthesis in plants, which then are buried over time rather than decomposed because of the waterlogged nature of these habitats.

Greenhouse gas (GHG) fluxes vary between tidal habitats and within tidal habitats and are driven by a variety of factors such as seasonality, soil properties (e.g. carbon content, salinity) and aboveground biomass (e.g. Al-Haj et al., 2020, Hu et al., 2020). To capture the seasonal balance between emission and fixation, GHG flux measurements are required over a longer period of time – ideally over the course of at least an annual year. There are two main approaches to capture GHG fluxes across spatial and temporal scales: the static chamber technique and eddy covariance flux towers, which are largely complimentary (Shahan et al., 2020; Hill & Vargas, 2022). Flux towers provide an overall flux estimate for a given area at an ecosystem scale at a high temporal resolution, but they can miss differences in fluxes within an ecosystem at a fine-scale level (Shahan et al., 2020). Static chambers, on the other hand, tend to capture these fine-scale fluxes from particular areas or target vegetation and can also reveal localised ebullition events, which would be missed by flux towers. This method is also more likely to pick up relationships between environmental drivers and different GHG fluxes (Shahan et al., 2020). Operating static chambers, however, is labour-intensive and data are generally collected only monthly or weekly at best and the gaps between measurements need to be filled with modelling of environmental data obtained from weather stations.

There are different practical designs for the static chamber technique, and the choice and implementation of the design needs to be considered more carefully in tidal environments than terrestrial environments. This report reviews evidence in peer-reviewed papers on the different static chamber applications in tidal environments.

A total of 91 papers (Appendix 1 – Table A1) are included in this review which covers three broad habitat categories: saltmarsh, mangroves and ‘other tidal habitats’, which include a mix of wetlands, seagrass, tidal mudflats, swamps, lagoons and freshwater and brackish marshes. The latter were merged into one category for analysis purposes because not many studies have been completed for these habitats individually compared to saltmarshes and mangroves. The studies included in this review all applied the static chamber method for flux measurements but utilised different set-ups. The key points highlighted in this review for the set-up of static chambers are summarised in a 'Best Practice Summary' for saltmarshes in Section 5, which includes a graphic presentation (Figure 1) of what this looks like in the field.

2. Static chamber method – collars or no collars

The main consideration for static chambers is the inclusion or exclusion of collars in the technical design. A collar can form a base for a chamber, which is inserted to a specified depth into the ground. Chambers are then placed on top of the collars and an airtight seal is formed between them. Alternatively, chambers can be placed directly into the soil, where the wet mud forms the airtight seal for the chamber. To push collars firmly into the ground, roots usually must be cut, which then temporarily alters the functioning of that particular area as plants recover from the disturbance. Collars are therefore put into place several minutes (Li et al., 2021), hours (Verma et al., 2002, Shalini et al., 2006, Krithika et al., 2008) days (Huang et al., 2019) or weeks (Yamamoto et al., 2009, Martin et al., 2015) before the first flux measurements to allow the system to equilibrate. Chambers are then attached to collars and an airtight seal between them is applied to create a closed system for sampling. The seal can take many forms including a groove filled with water (e.g. Chauhan et al., 2008; Ding et al., 2022), closed-cell foam (Geoghegan et al., 2018) combined with a clamp (Cornell et al., 2007), a rubber seal (Ford et al., 2012) or silicon and tape (Huang et al., 2019, Sanders-DeMott et al., 2022). In rare occasions cutting the roots for collar insertion can cause plant stress (e.g. dieback). When this occurs, collars will need to be removed and installed in a new location (Moseman-Valtierrra et al., 2021).

Collars are usually left in the ground for the duration of the entire fieldwork period (e.g. Chmura et al., 2016, Tong et al., 2018, Sanders-DeMott et al., 2022); exceptions occur, where collars were removed after each sampling round due to fear of sediment built-up (Li et al., 2021) or where different locations were sampled with each sampling round (Emery et al., 2014).

The greatest advantage of using collars is that the soil is only disturbed once when they are first installed and the provision of an airtight seal between the chamber and the ecosystem. A disadvantage is that collars can create microclimates (more wind-sheltered and warmer than ambient temperature), in which vegetation community and plant height can change. This has been observed for collars in peatland environments (pers. observation) but is also reported in artificial warming experiments investigating climate change impacts on vegetation communities with open-top chambers for peatlands (e.g. Dieleman et al., 2014; Munir et al., 2015) and saltmarsh communities (e.g. Charles & Dukes, 2009; Gedan & Bertness, 2009). As time progresses and certain plant species take advantage of these altered conditions in collars, flux measurements from within collars can become less representative of the overall site conditions. The key here is to ensure that the collar rim is not taller than necessary (usually just a few centimetres).

Alternatively, flux measurements without collars can be made by directly pushing the chamber a few centimetres into the ground (usually shallower insertion compared to collars). Where very wet, fine-textured mud without much vegetation is present, the chamber can be pushed straight into the ground and a seal will be formed by the mud (Hutchinson & Livingston, 2001). In more vegetated areas the insertion of a knife to cut roots is often required as chambers will not be able to push through the resistance of the roots (Adams et al., 2012). The disturbance of the system is usually mitigated by leaving the chamber with an open top in place for at least 15 to 30 minutes (Allen et al., 2007; Konnerup et al., 2014; Livesley & Andrusiak, 2012; Zheng et al., 2018) and up to 45 or 60 minutes (Allen et al., 2011) or even an entire day (Chanda et al., 2014) prior to sampling. A lid is then secured to the top of the chamber, but care needs to be taken to ensure that an airtight seal is formed between the lid and the chamber. Alternatively, if the chamber has a lid sealed to it, then the entire closed chamber can be inserted into the soil, removed for a certain period of time to allow for soil stabilisation and can then be replaced (Gao et al., 2018).

With or without collars present, knowing the entire chamber volume is key for gas flux calculations. When collars are not used and chambers are inserted directly into the ground, the volume might differ between replicates and in between measurement rounds, depending on how far the chamber is actually pushed into the soil each time. Inconsistencies with chamber volume are mitigated by measuring and calculating the head space for each location and measurement round (Allen et al., 2007, Whigham et al., 2009, Iram et al., 2021).

3. Collars in tidal environments

The inclusion or exclusion of collars for measuring GHG fluxes with the static chamber technique differs significantly between tidal environments in the reviewed literature. About four out of five studies include collars in saltmarshes, whereas in mangrove systems about three quarters of studies do not utilise collars (Table 1). In the third mixed category the inclusion and exclusion are almost evenly split, whereas seagrass and mudflat studies tend to place chambers into the ground directly (e.g. Shalini et al., 2006; Wang et al., 2007) and tidal marshes (that are non-saltmarshes, e.g. Neubauer et al., 2000) place chambers on the collar base. Reviewed studies that include both mangroves and saltmarshes also do not use collars (e.g. Iram et al., 2021). None of the reviewed studies justify their chosen technical design. The clear distinction between habitats is probably due to the two main habitat characteristics: mudflats without or in between vegetation do not show much resistance to chambers placed directly into the sediment and an airtight seal is formed automatically by the wet mud just after inserting these for a few centimetres (Hutchinson & Livingston, 2001). Vegetated soil with roots would be harder to penetrate without cutting, and the base would need to be inserted slightly deeper to ensure an airtight seal with the environment. A permanent collar would therefore be advantageous to ensure that this increased disturbance only takes place once and not at every measurement round. Adams et al. (2012) report the requirement to pre-cut with a knife in more consolidated sediment compared to mudflats. Comer-Warner et al. (2022) deployed collars into saltmarsh three days prior to sampling but inserted chambers directly into mudflats on the day of flux measurements.

Table 1: Inclusion of collars in static chamber design by habitat type. 'Other' includes other tidal habitats such as seagrass, tidal mudflats, swamps, lagoons and freshwater, brackish marshes, and a mix of wetlands.

Habitat	Collar	No collar	Total
Saltmarsh	32	8	40
Mangrove	8	24	32
Other	8	11	19
Total	**48**	**43**	**91**

The application of collars in tidal environments requires certain considerations. The wave action from tidal water could potentially dislodge collars and wash them away;

however, this problem was never reported in any of the reviewed papers, it can therefore be assumed that this is a very small risk. Tidal movement transports water, sediment and debris; collars can become traps for all in between measurement rounds, which would alter the collar environment. To avoid this, holes are drilled into the collars at surface level, which are left open between measurements and through which inundation, water exchange and drainage can place (e.g. Olsson et al., 2015, Wilson et al., 2015). Whilst in peatland environments usually one hole on the downslope side is sufficient to allow for drainage, several holes are generally drilled into collars in tidal environments (e.g. Neubauer et al., 2000; Olsson et al., 2015; Sanders-DeMott et al., 2022), with up to 12 per collar used (Wilson et al., 2015). Multiple holes ensure regular water exchange and prevent sediment from building up inside the collars. Holes sizes range from 0.5 cm (Moseman-Valtierra et al., 2021) to 2.5 cm (Wilson et al., 2015). During measurements these are sealed with bungs. In some designs holes are also drilled into the below-ground collar section of the collar to allow for pore-water drainage and equilibration (Weston et al., 2014; Sanders-DeMott et al., 2022).

The depth to which collars are installed into the soil should be a balance between minimising root disturbance, whilst providing a secure anchor to withstand tidal conditions at the same time. Most studies that use collars (30 out of 38 studies that reported collar depth) inserted these between 2 and 10 cm into the ground (e.g. Cabezas et al. 2008; Emery et al., 2014; Wang et al., 2021), whilst some are pushed in as deep as 19 to 28 cm (Tong et al., 2013; Shahan et al., 2022) and even up to 40 cm (Weston et al., 2014).

The height at which the collars emerge above ground is quite variable. This will depend on the combined collar-chamber height required for the different vegetation types and the actual chamber height. Collar heights range between 0 cm, where the collar is pushed all the way into the ground and a seal is created by a groove filled with water (e.g. Chauhan et al., 2008; Emery et al., 2014; Sun et al., 2014) and over 2 m, where tall Spartina alterniflora dominated the site (Geoghegan et al., 2018). The majority of studies (19 out of 32 that reported collar height), however, have a collar height ranging between 1 and 20 cm (e.g. Ford et al., 2012, Weston et al., 2014, Comer-Warner et al., 2022).

4. General considerations

Irrespective of habitat type and tidal conditions, a few further points require consideration. Trampling around the sampling sites can impact vegetation and flux measurements, therefore some form of boardwalk should be in place to spread the weight of the fieldworker across a larger area (e.g. Hirota et a., 2007; Olsson et al., 2015; Yang et al., 2019).

Mixing of air during measurements inside chambers is crucial to ensure that measurements are representative of the flux occurring, therefore handheld fans are usually placed inside the chamber (e.g. Allen et al., 2011; Li et al., 2021; Comer-Warner et al., 2022).

Chamber volume needs to be determined for flux calculations and this takes into account the volume of the chamber and the collar base – if used – combined. Vegetation inside the collars or measurement areas will reduce the overall air volume but the extent of this cannot be accurately determined without the destructive cutting and harvesting of the vegetation. Therefore, chamber volume is usually determined without vegetation volume. Sanders-DeMott et al., (2022) calculated that the flux error between an empty chamber and a vegetated chamber is less than 2.5%, therefore relatively negligible. Flux calculations can therefore be based on an empty chamber, especially where vegetation is low and vegetation volume is even across study sites. In this case a small error would occur consistently across all locations.

The greatest limitation of static chamber measurements is the lack of high frequency measurements that can take place due to the labour-intensive effort that is required. One way to compensate for this is the application of shade clothes. Net CO_2 flux is strongly related to the rate of photosynthesis carried out by plants (in combination with other factors), which in turn is dictated by photosynthetic active radiation (PAR) available at any given time (Planas-Clarke et al., 2020, Vázquez-Lule & Vargas, 2021). The application of shade clothes generates more data during a single measurement round by replicating different light levels through which a light response curve can be calculated. This will add data points to overall annual flux calculations. Actual measurements can be at a range of light levels, examples include three levels (light, intermediate and dark, Neubauer et al., 2000), four levels (100, 50, 25 and 0 % of ambient light, Weston et al., 2014) or up to as many as nine levels (0, 30, 40, 50, 60, 70, 80, 90, 100 % of ambient light, Planas-Clarke et al., 2020). Photosynthetically active radiation (PAR) is then measured inside the chamber

(Weston et al., 2014) to determine what actual light levels were present during each flux measurement.

When more than one measurement is taken per location (e.g. through the application of shade clothes), the chamber should be flushed between measurements to ensure that each flux measurement starts with ambient gas concentrations (Yi Lu et al., 1999).

Flux calculations require air temperature and pressure data, these should therefore be recorded during flux measurements. Temperature can change rapidly within the chamber, which can change the pressure inside the chamber. A vent tube is often used to maintain equilibrium gas pressure between the ambient atmospheric pressure and inside of the chamber (e.g. Alford et al., 1997, Comer-Warner et al., 2022).

Whilst an air temperature increase during light measurements is inevitable, during dark measurements this is often prevented by covering the chamber with aluminium foil (Wang et al., 2007; Olsson et al., 2015), a different reflective cover (Cornell et al., 2007, Chmura et al., 2016) and sometimes by adding insulating material to these (Comer-Warner et al., 2022, Ding et al., 2022).

5. Summary

A best practice summary for setting up GHG flux measurements with static chambers in a saltmarsh environment is presented here, which includes a graphic presentation of what this looks like in the field (Figure 1).

1. Collar preparation
    - Collars should be used in vegetated saltmarsh to ensure that disturbance to soil and vegetation only occurs once at the beginning of the flux measurements
    - Collar below-ground depth should be sufficient to provide a secure anchor to resist tidal action (ca. 2 to 10 cm)
    - Collar above-ground height should only be as tall as required for an air-tight seal to be applied to ensure that a microclimate is not created by the collar (not taller than 10 cm)
    - Collars should be prepared with several drainage holes (ideally a minimum of four to six) for water and sediment exchange between sampling rounds
2. Chamber design
    - Chamber height will be determined by vegetation height
    - Chambers should include a vent tube for pressure equilibration, the outlet of which needs to be covered to prevent air from escaping
    - Collar or chamber design (or both) should consider how an airtight seal between these two sections will be formed
    - If the chamber is an open-top chamber, then chamber design should also consider how an airtight seal between chamber and lid will be formed
    - Chamber design should allow for the application of a fan for mixing air, and for measuring air temperature within the chamber
    - Measurements for atmospheric pressure and PAR are also required

3. Measurement protocol
    - Seal drainage holes with bungs
    - Place fan inside the chamber and turn on
    - Attach chamber to collar and create an airtight seal
    - If chamber has an open top, attach lid to chamber with an airtight seal
    - Carry out greenhouse gas flux measurements
    - Remove lid or chamber for a set period of time to allow chamber air to return to ambient air
    - Apply shade cloth

- Carry on with flux measurements, flushing of chamber between measurements and shade cloth application for as often as required

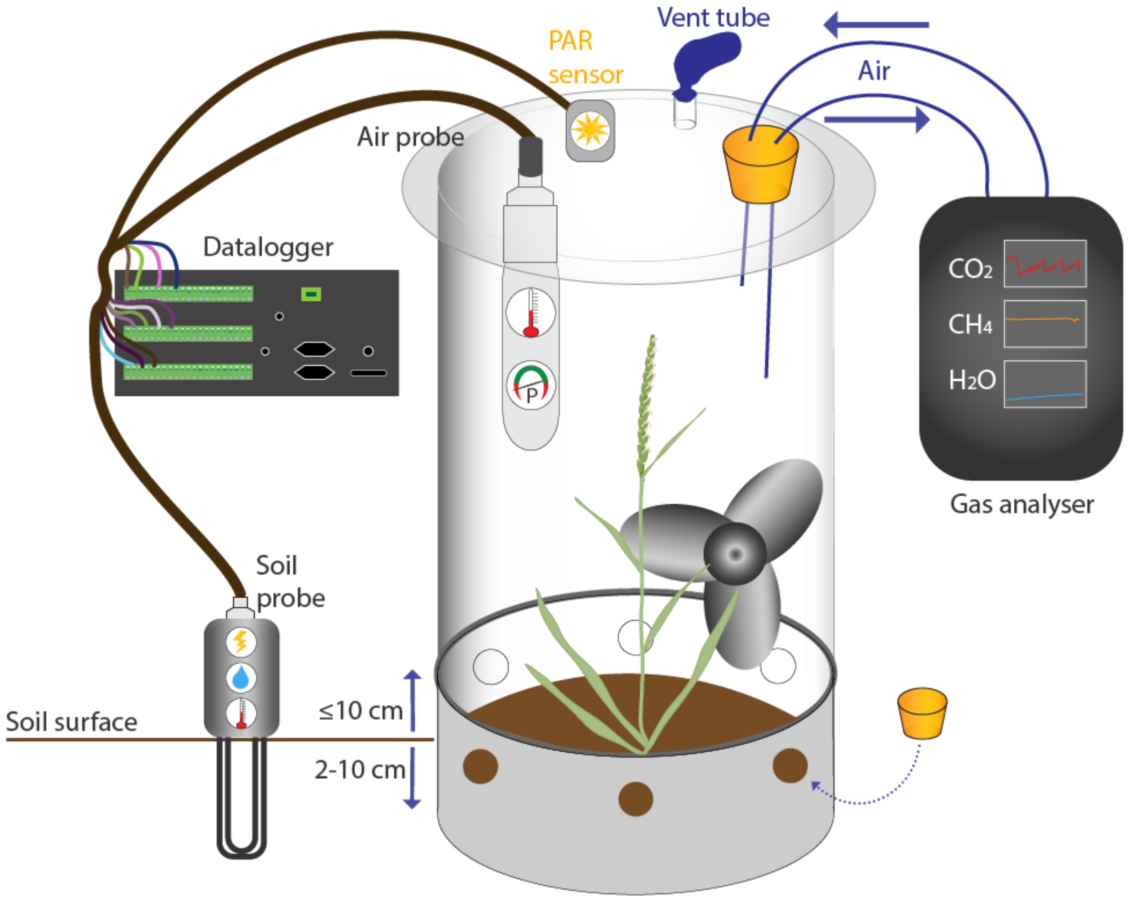

Figure 1: Graphical summary of recommended static chamber measurements in saltmarshes as applied for the WWF project GB100610. Additional measurements include soil moisture, soil temperature and electrical conductivity; these are additional environmental variables that are not a requirement for flux measurements. A battery-powered data logger logs all environmental data, but they could also be measured manually and recorded by hand in the field.

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Appendix 1 – Overview of reviewed papers

Table A1: List of the 91 published papers included in the review.

Citation	Location	Habitat	Dominant vegetation	Collar used (Y/N)
Adams et al., 2012	Blackwater estuary, Essex, UK	Saltmarsh	*Atriplex portuacoides, Salicornia spp., Spartina spp., Aster tripolium, Puccinellia maritima*	N
Alford et al., 1997	Lousiana, USA	Saltmarsh	*Spartina patens, Sagittaria lancifolia*	Y
Allen et al., 2007	Moreton Bay, Queensland, Australia	Mangrove	*Avicennia marina*	N
Allen et al., 2011	Moreton Bay, Queensland, Australia	Mangrove	*Avicennia marina*	N
Alongi et al., 2005	Jiulonjian Estuary, China	Mangrove	*Kandelia candel*	N
Alongi et al., 2008	Sumatra and Sulawesi, Indonesia	Mangrove	*Avicennia marina, Avicennia officinalis, Rhizophora stylosa, Rhizophora apiculata, Sonneratia caseolaris, Sonneratia lanceolata, Lumnitzera racemosa*	N
Bahlmann et al., 2015	Ria Formosa Lagoon, Portugal	Seagrass	*Zostera noltii*	N
Barnes et al., 2006	Wright Myo, India	Mangrove	*Rhizophora*	Y

Bartlett et al., 1985	USA (Virginia, Delaware, South Carolina, Georgia, Florida)	Saltmarsh	*Juncus roemerianus & Spartina alterniflora*	N
Bartlett et al., 1987	Virginia, USA	Saltmarsh	*Spartina alterniflora, Spartina cynosuroides*	N
Bartlett et al., 1989	Everglades, Florida, USA	Swamp and Marsh (Mangrove)	*Rhizophora mangle, Taxodium, Eleocharis, Cladium iamaicense, Muhlenbergia filipes*	N
Bauza et al., 2002	Magueyes Island, Puerto Rico	Mangrove	*Rhizophora mangle*	N
Burden et al., 2013	Tollesbury, Blackwater Estuary, UK	Saltmarsh	*Puccinellia maritima, Limonium vulgare, Salicornia europaea, Sarcocornia perennes*	N
Cabezas et al., 2018	Naples Bay, Florida, USA	Mangrove	*Rhizophora mangle, Avicennia germinans, Laguncularia racemosa*	Y
Cameron et al., 2019	Tanakeke Island and Tiwoho, Indonesia	Mangrove	*Rhizophora stylosa, Ceriops tagal, Rhizophora apiculata, Bruguiera gymnorrhiza, Sonneratia alba*	N
Chanda et al., 2014	Indian Sundarbans, India	Mangrove	*Aegiceras corniculatum, Aegialitis rotundifolia, Avicennia alba, Bruguiera gymnorrhiza, Avicennia marina, Excoecaria agallocha, Phoenix paludosa*	N

Chauhan et al., 2008	Bhitarkanika mangrove, Sunderbans, Godavari mangrove, Pichavaram mangrove, Muthupet mangrove, India	Mangrove	Mixed	Y
Chauhan et al., 2015	Gupti, Khola, Dharma, India	Mangrove	*Heritiera sp., Rhizophora mucronata, Exoecaria agallocha, Acanthus illicifolius, aonneratia apetala, Heritiera minor, Sonneratia sp., Rhizophora apiculata, Rhizophora mucronata, Avicennia sp.*	N
Chen et al., 2010	Futian Mangrove Nature Reserve, Mai Po, Sha Kong Tsuen, Yung Shue O, China	Mangrove	*Kandelia obovata, Acanthus ilicifolius, Bruguiera gymnorrhiza*	N
Chen et al., 2012	Mai Po Swamp, Hong Kong, China	Mangrove	*Kandelia obovata, Acanthus ilicifolius*	N
Chen et al., 2014	Teremaal, Indonesia	Mangrove	*Rhizophora apiculata, Bruguiera gymnorrhiza, Sonnertia alba*	N
Chmura et al., 2016	Dipper Harbour marsh, Bay of Fundy, Kouchibouguac marsh, Gulf of St. Lawrence, Canada	Saltmarsh	*Spartina patens*	Y

Comer-Warner et al., 2022	St. Lawrence estuary, La Pocatiere, Quebec, Canada	Saltmarsh & Mudflats	*Spartina spp., Phragmites australis*	Y
Cornell et al., 2007	North Carolina, USA	Saltmarsh	*Spartina alterniflora*	Y
Corredor et al., 1999	Magueyes Island, Puerto Rico	Mangrove	*Rhizophora mangle*	N
Dausse et al., 2012	Dyfi River, Ceredigion, UK	Saltmarsh	*Agrostis stolonifera, Festuca rubra, Puccinella maritima, Spartina anglica*	N
DeLaune et al., 1983	Barataria Basin, Louisiana, USA	Saltmarsh	*Spartina spp. & Panicum hemitomon*	Y
Dutta et al., 2017	Lothian Island, Sundarbans, India	Mangrove	*Avicennia alba, Avicennia marina, Avicennia officinalis, Excoecaria agallocha, Ceriops decandra*	N
Diefenderfer et al., 2018	Sequim Bay, Washington, USA	Saltmarsh	*Sarcocornia perennis*	Y
Ding et al., 2022	Yanghe River, Jiaozhou Bay, Shandong, China	Saltmarsh	*Spartina alterniflora*	Y
Emery & Fulweiler, 2014	Rough Meadows, Massachusetts, USA	Saltmarsh	*Phragmites australis, Spartina alterniflora*	Y
Ferron et al., 2009	Rio San Pedro, Bay of Cadiz,Spain	Saltmarsh	*n/a*	N

Ford et al., 2012	Crossens Marsh, UK	Saltmarsh	*Festuca rubra, Elytrigia repens* (NVCs SM16d & SM28)	Y
Gao et al., 2018	Zhangjiang River Estuary Mangrove National Naturk Reserve, China	Saltmarsh & Mangrove	*Spartina alterniflora, Kandelia obovata, Avicennia marina*	N
Geoghegan et al., 2018	Great Marsh, Rowley, MA, USA	Saltmarsh	*Spartina alterniflora* & *Spartina patens*	Y
Harriss et al., 1988	Everglades, Florida, USA	Mangrove	*Rhizophora mangle, Laguncularia racemosa, Avicennia germians, Conocarpus erectus*	N
Hirota et al., 2007	Lake Nakaumi, Japan	Saltmarsh	*Phragmites australis, Solidago altissima, Carex rugulosa*	Y
Huang et al., 2019	Min River Estuary, China	Brackish tidal marsh	*Cyperus malaccensis*	Y
Iram et al., 2021	Herbert River catchment, Queensland, Australia	Saltmarsh & Mangrove	*Suaeda salsa* & *Sporobolus* spp., *Avicennia marina*	N
Konnerup et al., 2014	Cienega Grande de Santa Marta, Colombia	Mangrove	*Avicennia germinans, Laguncularia racemosa, Rhizophora mangle, Batis maritime, Sesuvium portulacastrum*	N
Krauss & Whitbeck, 2012	Savannah River, South Carolina, USA	Tidal Swamp	*Taxodium distichum, Nyssa aquatica*	Y

Kreuzwieser et al., 2003	Queensland, Australia	Mangrove	*Avicennia marina, Rhizophora stylosa, Bruguiera sp.*	N
Krithika et al., 2008	Muthupet mangrove, India	Mangrove	*Avicennia marina*	Y
Krupadam et al., 2007	Godavari mangrove, India	Mangrove	*Rhizophora mucronata and Avicennia spp.*	Y
Lekphet et al., 2005	Ranong, Thailand	Mangrove	*Rhizophora apiculata*	N
Li et al., 2018	Dongtan wetland, China	Saltmarsh	*Phragmites australis, Scirpus mariqueter, Spartina alterniflora*	Y
Li et al., 2021	Chongming island, Yangtze estuary, China	Saltmarsh	*Phragmites australis, Scirpus mariqueter*	Y
Livesley & Andrusiak, 2012	Westernport Bay, Victoria, Australia	Saltmarsh & Mangrove	*Sclerostegia* spp., *Salicornia* spp., *Avicennia marina*	N
Lyimo et al., 2002	Mtoni mangrove forest, Dar es Salaam, Tanzania	Mangrove	*Rhizophora mucronata, Avicennia marina and Sonneratia alba*	N
Magenheimer et al., 1996	Dipper Harbor, Canada	Saltmarsh	*Spartina alterniflora, Plantago maritima, Spartina patens, Carx, Juncus spp., Eleocharis, Triglochin*	Y
Martin et al., 2015	Narragansett Bay, Rhode Island and Waquoit, Massachussetts, USA	Saltmarsh	*Phragmites australis, Spartina patens, Distichlis spicata*	Y

Middelburg et al., 1995	Scheldt Estuary, Netherlands	Intertidal mudflat	*n/a*	N
Migne et al., 2016	Arcachon Bay, French Atlantic Coast, France	Seagrass & Mudflat	*Zostera noltei* & bare	N
Moore et al., 1994	Hudson Bay, Ontario, Canada	Coastal Marsh (& other wetlands)	*Scirpus americanus, Festuca rubra, Carex palacea, Eleocharis palustris, Juncus balticus, Cythara glareosa, Menyanthes trifoliata*	N
Moseman-Valtierra et al., 2021	Narragansett Bay, Rhode Island, USA	Saltmarsh	*Spartina alterniflora*	Y
Munoz-Hincapie et al., 2002	Puerto Rico	Mangrove	*Rhizophora mangle*	N
Neubauer et al., 2000	Sweet Hall Marsh, York River, Virginia,USA	Tidal freshwater marsh	*Peltandra virginica, Pontederia cordata, Zizania aquatica*	Y
Nobrega et al., 2016	Ceara state, Brazil	Mangrove	*Rhizophora* spp.	N
Olsson et al., 2015	Liaohe river delta, China	Saltmarsh	*Phragmites australis, Suaeda salsa*	Y
Oremland et al., 1975	Florida, USA, Bimini, Bahamas	Seagrass	*Thalassia testudinum, Syringodium filiforme*	N
Purvaja et al., 2004	Pichavaram mangrove, India	Mangrove	*Avicennia marina, Avicennia officinalis, Excoecaria agallocha, Rhizophora apiculata and Rhizophora mucronata*	Y

Reid et al., 2013	Marsh Resource Meadowlands Mitigation Bank, Hackensack River Estuary, New Jersey, USA	Saltmarsh	*Spartina alterniflora, Phragmites australis*	Y
Robinson et al., 1998	River Colne Essex, UK	Intertidal mudflat	*n/a*	N
Sanders-DeMott et al., 2022	Herring River, Cape Cod, MA, USA	Saltmarsh	*Phragmites australis*	Y
Seyfferth et al., 2020	St. Jones Reserve, Dover, Delaware, USA	Saltmarsh	*Spartina alterniflora*	Y
Shahan et al., 2022	Mount Eden Creek Marsh, Hayward and Union City, California, USA	Saltmarsh	*Salicornia pacifica, Spartina foliosa*	Y
Shalini et al., 2006	Pulicat Lake, India	Seagrass	*Halophila ovalis, Enteromorpha, Chaetomorpha*	Y
Smith et al., 1999	Barataria Basin, Lousiana, USA	Saltmarsh	*Spartina alterniflora, Spartina patens, Panicum hemitomon*	Y
Sotomayor et al., 1994	Puerto Rico	Mangrove	*Rhizophora mangle, Avicennia germinans, Laguncularia racemosa*	N
Sun et al., 2013	Yellow River Estuary, China	Saltmarsh	*Suaeda salsa, Phragmites australis, Triatthena sacchariflora, Tamarix chinensis, Imperata cylindrica*	Y

Sun et al., 2014	Yellow River estuary, Dongying City, Shandong, China	Saltmarsh	*Suaeda salsa, Phragmites australis, Tamarix chinensis*	Y
Tong et al., 2010	Min River Estaury, China	Saltmarsh	*Phragmites australis*	Y
Tong et al., 2013	Shanyutan wetlands, Min River estuary, China	Saltmarsh	*Phragmites australis, Cyperus maloaccensis*	Y
Tong et al., 2018	Shanyutan wetland, Min River	Saltmarsh	*Spartina alterniflora, Cyperus malaccensis*	Y
Verma et al., 2002	Vembanad Lake, India	Coastal Lagoon	*n/a*	Y
Wang et al., 2007	Yinyang, Chongming Island, Gulu, Bailonggang, Chaoyang, Laogang, Yangtze River, China	Intertidal mudflat	*n/a*	N
Wang et al., 2016	Yancheng National Natural Reserve, Jiangsu, China	Mangrove	*Spartina alterniflora, Kandelia obovata*	Y
Wang et al., 2017	Jiulong River Estuary, Zhangzhou City, Fujian, China	Saltmarsh	*Phragmites australis,Imperata cylindrica, Aeluropeus littoralis, Spartina alterniflora, Suaeda salsa,*	N
Wang et al., 2018	Carpenteria Salt Marsh Reserve, California, USA	Saltmarsh	*Sarcocornia pacifica*	Y

Wang et al., 2021	Carpinteria Salt Marsh Reserve, California, USA	Saltmarsh	*Spartina alterniflora, Spartina patens, Phragmites australis, Distichlis spicata*	Y
Wei et al., 2020	Yellow River Delta, northern China, China	Saltmarsh	*Suaeda salsa*	N
Welti et al., 2017	North Stradbroke Island, Queensland, Australia	Mangrove	*Rhizophora stylosa, Avicennia marina*	Y
Weston et al., 2014	Delaware River Estuary (several sites), USA	Tidal marshes	*Peltandra virginica, Zizania aquatica, Spartina alterniflora, Bidens* spp., *Amaranthus* spp., *Polygonum* spp.	Y
Whigham et al., 2009	Indian River Lagoon, North Hutchinson Island, Florida, USA	Mangrove	*Avicennia germinans, Laguncularia racemosa, Conocarpus erecta, Batis maritima*	N
Wilson et al., 2015	Dauphin Island, Alabama	Saltmarsh	*Spartina alterniflora, Cladium jamaicense, Juncus roemerianus*	Y
Xu et al., 2014	Yancheng National Nature Reserve, Jiangsu, China	Saltmarsh	*Spartina alterniflora*	Y
Yamamoto et al., 2009	Lake Obuchi, Aomori Prefecture, Japan	Brackish marsh	*Phragmites australis, Juncus yokoscensis, Miscanthus sinensis, Cirsium inundatum*	Y
Yang et al., 2019	Shanyutan wetland, Min River, China	Saltmarsh	*Cyperus malaccensis, Phragmites australis, Spartina alterniflora*	Y

Yi Lu et al., 1999	Hainan Island, China	Mangrove	*Bruguiera sexangula, Bruguiera gymnorhiza, Rhizophora stylosa*	N
Yu et al., 2012	Dongtang wetland, Chonming Island, Yangtze River, China	Saltmarsh	*Scirpus mariqueter*	Y
Zheng et al., 2018	Zhangjiang River Estuary Mangrove National Naturk Reserve and Qinglan Harbour Mangrove Provincial Natural Reserve, China	Mangrove	*Kandelia obovata, Aegiceras corniculatum, Avicennia marina, Bruguiera sexangula, Sonneratia caseolaria, Lumnitzera racemosa, Cerips togal, Rhizophora apiculata*	N

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