Ecosystem Pushing: Coral Restoration in Refugia as an Unexplored Answer to Climate Change Adaptation

Edith Maria Mertz¹ and Anne McDonald²

1 PhD candidate, Sophia University, Tokyo, Japan
2 Professor, Sophia University, Tokyo, Japan
E-mail: mertz.em@gmail.com

Abstract. Climate change is driving ecosystem change across the biosphere on an unprecedented scale. Large biogeographic shifts are underway as habitats move their ranges towards the poles in an attempt to remain in zones that adhere to organisms’ preferred temperature ranges. These new areas of shifting climatic ranges, or refugia, represent important opportunities for the future survival of countless species in a warming world. However, many species may have colonisation rates too slow to keep up with climate change. This may be due to barriers to dispersal, long time periods in reproductive cycles, survival and viability of offspring, geographic isolation of suitable new habitats, stochasticity and other environmental factors. Ecosystem pushing proposes to propagate species into refugia using restoration techniques with the aim of supporting species survival and ecosystem conservation. This paper proposes ecosystem pushing as a new management intervention for the field of coral reef restoration. Management considerations will need to include geographic models of refugia projections to ascertain appropriate locations for restoration work. Other important considerations would include assessing the risks of losing one ecosystem type for another, invasive species and disease introductions, issues of intervention scale and time constraints, and levels of stakeholder engagement with local communities.

1. Introduction
Climate change along with ocean acidification and other anthropogenic pressures are driving large scale ecosystem changes across the biosphere [1]. Ecoregions and habitats are shifting geographically and there is a well documented movement of ecosystem ranges toward the polar regions underway [1,2,3]. The concept of refugia plays a key role in this. Keppel et al., 2012 [4] define refugia as “habitats that components of biodiversity retreat to, persist in and can potentially expand from under changing environmental conditions”. In this paper refugia are referred to specifically within the context of thermal shifts due to climate change. Many marine ecosystems are endangered and their ranges are shrinking faster than they are expanding into refugia [5,6]. This may be due to slow rates of colonisation, such as in the case of most corals, which can be exacerbated by the fact that large distances between ‘islands’ of newly suitable refugia often exist [6]. Corals may not be expanding into refugia due to barriers to dispersal such as physical barriers or prevailing currents preventing larvae from reaching refugia [7]. There may be biological constraints such as long time periods in reproductive cycles, larval type, mortality and competency characteristics [7]. Another possible reason could be that other limiting factors exist such as reduced light incidence levels at higher latitudes [8]. Lastly, the frequency of chance events such as long range dispersal due to unusual current fluctuations carrying coral larvae may play a role [7]. Corals are therefore an example of how natural rates of colonisation could be too slow for many threatened ecosystems to expand their ranges and survive into the future alongside climate change [5].
Current rates of decline show that we have already lost half of all corals worldwide and that coral ecosystems may go globally extinct by the year 2050 [9]. Corals represent a critically important ecosystem, not only in terms of biodiversity but also for supporting human livelihoods and local economies [10].

Human interventions such as artificial reef building and other restoration techniques may well prove to be the key factor in perpetuating endangered marine ecosystems into the future [6] and supporting global fisheries and human livelihoods [11]. Management interventions specifically enhancing range extensions into refugia made recently available due to climate change carry with them new considerations for conservationists and policy makers. The risk of introducing alien invasive species to other vulnerable and endangered ecosystems would be of primary concern [12]. Managers would have to consider carefully the potential appropriateness and levels of urgency of ecosystem types to be transplanted vs the risks of degradation and loss of existing ecosystems [12]. Such assisted migration projects, or ecosystem pushing projects, are practically unheard of even though managers have realized that the race against climate change is urgent [13,14,15]. The stakes for conservation are potentially high with ecosystem pushing and this new field requires that policy guidelines be developed for managers to reflect responsibly the chief practical and ethical dilemmas that mankind has brought upon itself along with climate change [12]. From a global perspective there is also an urgent need to identify key hotspot areas of refugia range extensions for coral reefs and assess what additional resources are needed to ensure the survival of this key marine ecosystem to the year 2050. If global effort is to be undertaken in time scientific research on ecosystem pushing needs to mobilize discussion forums in global decision making urgently.

2. Poleward shifts of climatic zones and organism ranges

Current trends showing poleward shifts of climatic zones and the concurrent range responses or migration of organisms are well documented [1,3,16,17,18]. A multitude of species across a large range of taxa have been observed to change their habitat ranges in response to warming temperatures and/or changes in rainfall patterns linked to climate change (see table 1 for a list of taxa and their references).

These range extensions into refugia have also been observed in corals [19,20,21]. Overall corals appear to have increased recruitment in subtropical latitudes and reduced recruitment in the tropics [21]. Another study found that range extensions in corals occurred in temperate waters while in contrast subtropical corals appeared not to be expanding their ranges poleward [20]. It remains unclear why exactly some coral species show a tendency to propagate into refugia while others do not (see the introduction for a list of possible reasons).

Table 1: Publication list of biological groups that have exhibited poleward shifts in their biogeographical ranges. This list is not exhaustive but serves to exemplify the scope of taxa involved.

| Biological group | Publication | Key findings on poleward range extensions |
|------------------|-------------|------------------------------------------|
| Vegetation types | [18]        | Comparisons of historical to contemporary photographs of Arctic vegetation showed that treelines had moved and shrub growth had expanded into areas previously free of shrubs. Growth had increased along latitudinal temperature gradients. |
| Birds            | [22]        | During a 20 year period many British bird species moved the Northern margins of their ranges Northward by an average of 18.9km. |
Butterflies [23] 22 non-migratory European butterflies were found to have shifted their ranges North by 35-240km during this century.

Marine zooplankton [24] The distribution of both plankton and intertidal organisms changed significantly during periods of ocean warming in British waters showing latitudinal shifts of up to 193km.

Intertidal invertebrates [25] Comparing the macroinvertebrate abundances between surveys conducted 60 years apart showed changes in relation to geographic range of 46 species. Southern species were found to have migrated Northward.

Fish [26] Over a 20 year period at two sites off of Los Angeles, USA, species composition shifted in dominance from Northern to Southern reef fish species.

Amphibians [27] Range maps of survey data from Illinois, USA, conducted almost 40 years apart showed that herpetological range expansions were primarily Northward and attributable to warming climatic conditions.

Mammals [28] Red fox range expansion pushing it into the range of Arctic foxes in North America and Eurasia was associated with climate related changes in food availability.

Corals [20][21] Corals in Japan were found to be expanding their ranges Northward in temperate regions. Globally coral recruitment was found to have increased in subtropical latitudes and decreased in the tropics.

However, species do not exist in isolation and entire ecosystem types and bioregions are shifting geographically towards the poles [1,3,16,17,29]. For instance vegetation types in the Arctic are on the increase in terms of biomass and their extension Northwards [18]. Migration rates are projected to be higher in boreal and temperate biomes than in tropical ones [3]. However, it is estimated that under a doubled CO$_2$ climate forcing model that migration rates will be too slow to keep up with climate change and will lead to a situation where highly mobile and opportunistic species are selected for, while biodiversity overall will be in decline [3].

3. Responsiveness of coral restoration

Site selection for coral restoration projects is strongly linked to success or failure of projects [30]. A review by Bayraktarov et al. (2016) [30] on the economics and feasibility of marine restoration projects found that unsuitable sites tended to be characterised by altered hydrological conditions, high wave and flow energy and inadequate substrate. The authors recommended that restoration sites be located where historical reports of the presence of the ecosystem existed, and that a full understanding of the abiotic conditions and whether they could support the marine coastal ecosystem needs to be achieved before any restoration action can be undertaken [30]. Locating restoration work in sites that historically supported coral can indeed be a successful strategy [31].

However, this does not take into consideration the possibility that abiotic factors might have changed at the site, perhaps causing the loss of the ecosystem in the first place. Indeed, the second point, that managers should be fully aware of the abiotic conditions needed to support coral reefs, becomes critical.
when we consider that climate change has already altered the geographical picture of climatic zones. Sea surface temperature was found to play an important role in the survival of coral restoration outplants and temperature can be an important factor to consider when determining where to place restoration sites [32]. However, an exhaustive search through published studies on coral restoration could uncover no mention of potential restoration site locations with regards to refugia, although one study vaguely suggested that this may be a factor to take into account [33]. Critically, managers do not appear to be considering the possibility that new areas of favourable abiotic conditions may exist in the form of refugia for coral reefs, where propagated coral in restoration sites would likely have higher chances of survival. This potential oversight needs to be addressed by additional modelling of refugia for coral reefs globally so as to identify which areas of the world provide the best chances for corals to persist into the future. Some studies have modelled refugia for coral reefs [34,35,36]. Such areas could become priority locations for coral reef propagation projects. Doing so would consolidate restoration efforts into a model that is globally more responsive to climate change impacts on coral reefs.

4. Ecosystem pushing as a management option

4.1. Defining ecosystem pushing

The idea of performing propagation or restoration work in refugia has not received attention in published literature until recently [15]. For the purposes of this paper the concept of ecosystem pushing, or assisted migration is defined as the active intervention by man using restoration techniques to accelerate the natural rate of extension of ecosystems into newly available niche zones or refugia created by climate change. This concept is similar to traditional restoration but differs from it in one key aspect: it seeks to assist ecosystems or species to keep up with the rate of shifting geographical climate zones, due to climate change, where they may not otherwise be capable of doing so.

4.2. Parallels with afforestation and reforestation

Afforestation generally seeks to expand areas planted with trees and is most often practiced for commercial timber production [37]. China hosts the world’s largest plantation style afforestation project which saw trees being planted between 1978 and 2003 in 23.5 million ha of grassland [38]. This type of project has been employed with the purposes of mitigating climate change and desertification, but these efforts have most often not included climate modelling in their approaches to select sites for afforestation [38]. Modelling for this purpose was conducted for *Pinus tabulaeformis*, an endemic species in China and one of the main tree species used for afforestation there [39], but no specific mention was made of the use of this species for afforestation in refugia. If afforestation in refugia does occur it is likely by chance and not as a specific goal. Additionally, plantations tend to be monoculture regimes and are generally not seen as supporting biodiversity if they replace natural vegetation [40,41,42]. This is because by design plantations are not implemented with the goal of recreating forest ecosystems and therefore cannot compare to the biodiversity that is lost from previously undisturbed habitats. As such afforestation has as yet to prove itself useful as a means to propagate forest ecosystems into refugia.

When biodiversity conservation is considered as a goal, however, reforestation or forest recreation projects constitute one of the most common types of restoration projects practiced globally [43,44]. Reforestation projects tend to focus on restoring areas that were previously forests but that have been degraded or completely transformed into, for example, cropland or grazing [43,44]. Forest restoration efforts do not appear to be targeting refugia and when they are this is likely accidental (for an example see [45]). Occasionally though reforestation projects do make mention of propagation into refugia and some literature citing the importance of this kind of action does exist [44,46]. Wilkin et al. (2016) [44] point out that forest refugia deserve special consideration for restoration and fuels management for climate change adaptation, although they only considered refugia that spanned existing forest areas and did not consider the possibility of expanding forests into refugia on unforested land. They concluded that refugia are not static and are highly complex which poses additional decision making challenges for managers [44]. As is the case for coral restoration, managers in forest restoration appear not to be
taking into consideration the fact that refugia may exist in neighbouring areas and that ecosystems are shifting geographically towards the poles due to climate change.

4.3. Risks

Ecosystem pushing carries with it several potential risks that managers would need to consider carefully. Habitat degradation is a risk if the receiving environment is in a near pristine state, high in biodiversity and/or provides significant environmental goods and services. Supplanting one ecosystem in favour of another should be done with careful and full consideration of what is being lost. However, if the receiving environment is degraded and will continue to be degraded by climate change and/or other anthropogenic impacts, creating a new ecosystem type in its place may likely create benefits for biodiversity and/or socioeconomics. There is also the risk of introducing invasive species or disease to sites. In the case of invasive species it may be argued that if the species would expand its range naturally in response to climate change then perhaps such range expansion should not be considered invasive per se, but the result of a natural adaptive process. Ecosystem pushing in such cases would simply serve to accelerate the speed of this natural process. Accurate models of the potential ranges of species would be critical for justifying artificial range expansion programs. Relocations of species very near to their original ranges, such as artificial expansion on the borders of their natural ranges, should be considered native expansions. Caution would be advised, however, and assisting long distance delocalized introductions of species would not be recommended. Introducing diseases does represent a significant risk if the receiving environment has species that are biologically similar to the species that are to be propagated into it. This would have to be mitigated with careful quarantine precautions or by selecting methods that exclude pathogens from propagated stock. Another risk is the potential to overharvest or harm donor organisms during harvesting. This is of particular concern for coral since overharvesting for restoration purposes has been known to significantly damage healthy reefs in some cases [47]. Collecting fragments of opportunity that have broken off due to storm action is one potential alternative to direct harvesting [47]. Another option is to grow stock from smaller samples separately to be transplanted in larger volumes later [47]. In terrestrial environments ecosystem pushing could lead to local effects on hydrology and/or fire regimes if there are significant changes in vegetation types. Careful consideration would be needed to ascertain if these changes would remain within an acceptable range. Finally, ecosystem pushing projects might carry with them some socioeconomic risks. Changes to the nature and volume of goods and services delivered by the environment could lead to changed land use, impacting livelihoods and benefits to cultural uses. Stakeholder engagement would be necessary to allow communities to determine if the potential benefits of the propagated ecosystem outweigh the losses from the existing environment.

4.4. Biodiversity conservation as a goal

Ecosystem pushing projects would seek to propagate habitat types and in the best case scenario support the recreation of ecosystems. Therefore biodiversity conservation is central to the concept and should be a core aim of any ecosystem pushing project. Restoration programs seeking to recreate ecosystems with the aim of maximizing biodiversity need to pay special attention to modelling and following patterns of succession. In many cases simply planting pioneer species is not enough to recreate ecosystems [43]. To aim for ecosystem recreation multiple phases of management action, using multiple species, would be required over long time periods and impacts on biodiversity would have to be considered at each step with careful monitoring. This should increase species richness especially in receiving ecosystems that are already low in biodiversity and degraded. To guide whether ecosystem pushing as a management action should be undertaken one could consider Aldo Leopold’s land ethic maxim [48] that: “A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise.” It is estimated that biodiversity losses due to climate change will be significant [49]. These losses will be increased if ecosystems that are attempting to expand their biogeographic ranges are not able to do so quickly enough to keep up with climate change [49]. Ecosystem pushing seeks to become a mitigating action that could assist ecosystems in
keeping up with the speed of climatic changes and therefore preserve a greater amount of biodiversity into the future.

4.5. Principles for responsible ecosystem pushing
With the risks and a central goal of maximising biodiversity in mind, this paper proposes several principles for responsible ecosystem pushing:

- Projects should prioritize highly threatened ecosystem types.
- Projects should expand habitat or species’ ranges only into refugium areas where the selected ecosystem could expand naturally due to climate change. Preferably there should be signs of attempted natural range expansion by biotic elements of the selected ecosystem in place.
- Projects should expand ecosystems into zones where the receiving ecosystem is being degraded due to climate change impacts.
- Projects should focus on localised range expansions for species introductions and avoid long distance delocalized range expansions to reduce the risk of introducing invasive species.
- Projects should mimic the natural process of succession as closely as possible by propagating multiple species in stages to prevent monoculture regimes from becoming the result.
- Projects should be long term in scope with monitoring of risk factors built in.

5. Conclusion
Ecosystem pushing is a novel concept that seeks to support the survival of ecosystems in the face of the challenges posed by climate change by the propagation of species, habitat types or ecosystems into refugia. It has some parallels with afforestation and reforestation but seeks to recreate ecosystems or habitat types instead of the propagation of monocultures, and would more specifically target refugia as appropriate propagation sites. Ecosystem pushing comes with some associated risks but these can be mitigated with careful consideration by managers. The risks are also likely not as significant as the large scale of biodiversity loss that has been projected will result from climate change in the future. Some ecosystem types such as coral reefs are especially biodiverse and also have large socio-economic importance, and should therefore be prioritized for conservation and ecosystem pushing projects. Focusing on refugia as locations for coral reef propagation will help to consolidate efforts globally in the currently fragmentary field of coral restoration.

6. References
[1] Gonzalez P, Neilson R P, Lenihan J M and Drapek R J 2010 Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change Global Ecology and Biogeography 19(6) 755-768
[2] Fischlin A, Midgley G F, Price J T, Leemans R, Gopal B, Turley C, Rounsevell M D A, Dube O P, Tarazona J and Velichko A A 2007 Ecosystems, their properties, goods, and services. In Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ed M L Parry, O F Canziani et al (Cambridge University Press, Cambridge) pp 211–272
[3] Malcolm J R, Markham A, Neilson R P and Garaci M 2002 Estimated migration rates under scenarios of global climate change Journal of Biogeography 29(7) 835-849
[4] Keppel G, Van Niel K P, Wardell - Johnson G W, Yates C J, Byrne M, Mucina L, Schut A G, Hopper S D and Franklin S E 2012 Refugia: identifying and understanding safe havens for biodiversity under climate change Global Ecology and Biogeography 21(4) 393-404
[5] Perry C T, Kench P S, Smithers S G, Riegl B, Yamano H and O’leary M J 2011 Implications of reef ecosystem change for the stability and maintenance of coral reef islands Global Change Biology 17(12) 3679-3696
[6] Muir P R, Wallace C C, Done T and Aguirre J D 2015 Limited scope for latitudinal extension of reef corals *Science* **348**(6239) 1135-1138

[7] Treml E A, Roberts J, Halpin P N, Possingham H P and Riginos C 2015 The emergent geography of biophysical dispersal barriers across the Indo - West Pacific *Diversity and Distributions* **21**(4) 465-476

[8] Kahng S E, Akkaynak D, Shlesinger T, Hochberg E J, Wiedenmann J, Tamir R and Tchernov D 2019 Light, temperature, photosynthesis, heterotrophy, and the lower depth limits of mesophotic coral ecosystems (MCEs). In *Mesophotic coral ecosystems*, ed Y Loya and K A Puglise (New York: Springer). pp. 801-828

[9] Pandolfi J M, Connolly S R, Marshall D J and Cohen A L 2011 Projecting coral reef futures under global warming and ocean acidification *Science* **333**(6041) 418-422

[10] Hoegh-Guldberg O, Mumby P J, Hooten A J, Steneck R S, Greenfield P, Gomez E, Harvell C D, Sale P F, Edwards A J, Caldeira K and Knowlton N 2007 Coral reefs under rapid climate change and ocean acidification *Science* **318**(5857) 1737-1742

[11] Lewis III R R 2005 Ecological engineering for successful management and restoration of mangrove forests *Ecological engineering* **24**(4) 403-418

[12] Veitch C R and Clout M N (Eds) 2002 *Turning the tide: The eradication of invasive species: Proceedings of the International Conference on Eradication of Island Invasives* vol 27, (Auckland, New Zealand: IUCN)

[13] McKay J K, Christian C E, Harrison S and Rice K J 2005 “How local is local?”—a review of practical and conceptual issues in the genetics of restoration *Restoration Ecology* **13**(3) 432-440

[14] Young C N, Schopmeyer S A and Lirman D 2012 A review of reef restoration and coral propagation using the threatened genus Acropora in the Caribbean and Western Atlantic *Bulletin of Marine Science* **88**(4) 1075-1098

[15] Palmer C, and Larson B M 2014 Should we move the whitebark pine? Assisted migration, ethics and global environmental change. *Environmental Values* **23**(6) 641-662

[16] IPCC 2007a *Climate Change 2007: The Physical Science basis*. (Cambridge University Press, Cambridge)

[17] IPCC 2007b *Climate Change 2007: Impacts, Adaptation, and vulnerability*. (Cambridge University Press, Cambridge)

[18] Sturm M, Racine C and Tape K 2001 Increasing shrub abundance in the Arctic *Nature* **411**(6837) 546-547

[19] Serrano E, Coma R, Ribes M, Weitzmann B, García M and Ballesteros E 2013 Rapid northward spread of a zooxanthellate coral enhanced by artificial structures and sea warming in the western Mediterranean *PLoS One* **8**(1) e52739

[20] Nakabayashi A, Yamakita T, Nakamura T, Aizawa H, Kitano Y F, Iguchi A, Yamano H, Nagai S, Agostini S, Teshima K M and Yasuda N 2019 The potential role of temperate Japanese regions as refugia for the coral Acropora hyacinthus in the face of climate change *Scientific reports* **9**(1) 1-12

[21] Price N N, Muko S, Legendre L, Steneck R, van Oppen M J, Albright R, Ang Jr P, Carpenter R C, Chui A P Y, Fan T Y and Gates R D 2019 Global biogeography of coral recruitment: tropical decline and subtropical increase *Marine Ecology Progress Series* **621** 1-17

[22] Thomas C D and Lennon J J 1999 Birds extend their ranges northwards *Nature* **399**(6733) 213-213

[23] Parmesan C, Ryholm N, Stefanescu C, Hill J K, Thomas C D, Descimon H, Huntley B, Kaila L, Kullberg J, Tammaru T and Tennent W J 1999 Poleward shifts in geographical ranges of butterfly species associated with regional warming *Nature* **399**(6736) 579-583

[24] Southward A J, Hawkins S J and Burrows M T 1995 Seventy years’ observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature *Journal of thermal Biology* **20**(1-2) 127-155

[25] Sagarin R D, Barry J P, Gilman S E and Baxter C H 1999 Climate - related change in an intertidal community over short and long time scales *Ecological monographs* **69**(4) 465-490
[26] Holbrook S J, Schmitt R J and Stephens Jr J S 1997 Changes in an assemblage of temperate reef fishes associated with a climate shift Ecological Applications 7(4) 1299-1310

[27] Tucker J K, Lamer J T and Dolan C R 2008 A northern range expansion for the green tree frog Hyla cinerea and trends in distributions of Illinois reptiles and amphibians Transactions of the Illinois State Academy of Science 101(1-2) 125-132

[28] Hersteinsson P and Macdonald D W 1992 Interspecific competition and the geographical distribution of red and Arctic foxes Vulpes vulpes and Alopex lagopus Oikos 64 505-515

[29] Rosenzweig C, Karoly D, Vicarelli M, Neofotis P, Wu Q, Casassa G, Menzel A, Root T L, Estrella N, Seguin B and Tryjanowski P 2008 Attributing physical and biological impacts to anthropogenic climate change Nature 453(7193) 353-357

[30] Bayraktarov E, Saunders M I, Abdullah S, Mills M, Beher J, Possingham H P, Mumby P J and Lovelock C E 2016 The cost and feasibility of marine coastal restoration Ecological Applications 26(4) 1055-1074

[31] Ogden-Fung C, Tsang A and Dwivedi V 2020 Site Selection for Coral Restoration in Maunalua Bay, O‘ahu. Report to NREM 601, Social-Ecological systems analysis of NREM

[32] Foo S A and Asner G P 2020 Sea surface temperature in coral reef restoration outcomes Environmental Research Letters 15(7) 074045

[33] Greer L, Clark T, Waggoner T, Busch J, Guilderson T P, Wirth K, Zhao J X and Curran H A 2020 Coral Gardens Reef, Belize: A refugium in the face of Caribbean-wide Acropora spp. coral decline PloS one 15(9) e0239267

[34] Cacciapaglia C and van Woesik R 2015 Reef - coral refugia in a rapidly changing ocean Global Change Biology 21(6) 2272-2282

[35] Van Hooijdonk R, Maynard J A and Planes S 2013 Temporary refugia for coral reefs in a warming world Nature Climate Change 3(5) 508-511

[36] Brockerhoff E G, Jactel H, Parrotta J A, Quine C P, and Sayer J 2008 Plantation forests and biodiversity: oxymoron or opportunity? Biodiversity and Conservation 17(5) 925-951

[37] Buscardo E, Smith G F, Kelly D L, Freitas H, Iremonger S, Mitchell F J, O’Donoghue S and McKee A M 2008 The early effects of afforestation on biodiversity of grasslands in Ireland. In Plantation Forests and Biodiversity: Oxymoron or Opportunity? (Springer, Dordrecht) pp 133-148

[38] Lachance D, Lavoie C, and Desrochers A 2005 The impact of peatland afforestation on plant and bird diversity in southeastern Québec Ecoscience 12(2) 161-171

[39] Wilkin K M, Ackerly D D and Stephens S L 2016 Climate change refugia, fire ecology and management Forests 7(4) 77

[40] Scarsbrook M R and Halliday J 1999 Transition from pasture to native forest land - use along stream continua: Effects on stream ecosystems and implications for restoration New Zealand Journal of Marine and Freshwater Research 33(2) 293-310

[41] Stella J C, Hayden M K, Battles J J, Piégay H, Dufour S and Fremier A K 2011 The role of abandoned channels as refugia for sustaining pioneer riparian forest ecosystems Ecosystems 14(5) 776-790
[47] Boström-Einarsson L, Babcock R C, Bayraktarov E, Ceccarelli D, Cook N, Ferse S C, Hancock B, Harrison P, Hein M, Shaver E and Smith A 2020 Coral restoration—A systematic review of current methods, successes, failures and future directions PloS one 15(1) e0226631
[48] Leopold A 1949 A sand county almanac (New York: Oxford University Press)
[49] Bellard C, Bertelsmeier C, Leadley P, Thuiller W, and Courchamp F 2012 Impacts of climate change on the future of biodiversity Ecology letters 15(4) 365-377

Acknowledgements

Financial support towards the completion of a PhD at Sophia University was provided by the Japanese Ministry of Education, Culture, Sports, Science and Technology’s MEXT scholarship.