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Cost-Benefit Analysis of Disaster Mitigation Infrastructure: The Case of Seawalls in Otsuchi, Japan

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Abstract

Disaster management problems often pose the same types of challenges that environmental governance problems do; they involve decision-makers at various levels and can transcend political boundaries. We conduct a benefit-cost analysis of a disaster adaptation strategy in Otsuchi, which was undertaken shortly after the 2011 Tohoku earthquake and tsunami devastated the region. Results indicate that present value net benefits from the planned seawall are positive, even if expected damages are low, provided that the wall is capable of reducing damage by at least 50%. A hybrid method of governance may, however, be effective at increasing the benefit-cost ratio.

JEL Classifications: D61; Q5

Keywords: tsunami, benefit-cost analysis, Otsuchi, seawall, Tohoku, governance

1. Introduction

The term "environmental governance" has been defined in many ways, often broadly to describe how people make decisions concerning natural resources. Some researchers have developed more specific definitions, such as "the set of regulatory processes and organizations through which political actors influence environmental actions and outcomes" (Lemos and Agrawal, 2006). Whether implicitly or explicitly stated, an important theme running through all of these definitions is that management is related to decision-makers at multiple levels.

While not a resource to be harvested per se, a natural disaster is an environmental occurrence that damages traditionally extracted natural resources. Moreover, disaster management problems often exhibit the same types of challenges that standard environmental governance problems do, e.g. they often involve decision-makers at various levels and can transcend local or even national political boundaries. In this paper, we examine a disaster adaptation strategy in Otsuchi, Japan.

After the Tohoku region was severely damaged by an earthquake and ensuing tsunami in 2011, the Japanese government moved forward with a multi-billion-dollar dike construction plan. We begin by conducting a benefit-cost analysis of the planned seawall, taking into account the probability of another Tohoku-like event, expected damages, and efficacy of damage reduction provided by the wall. We then consider alternative adaptation strategies suggested (but not implemented) by private citizens. We conclude by discussing how a hybrid method of governance (e.g. a public-private partnership) may be effective at increasing the benefit-cost ratio by lowering costs, while maintaining benefits.

2. Background and significance

Otsuchi is a city located in the Iwate Prefecture along Japan's Sanriku Coast (northeastern coast of Honshu). Prior to 2011, the primary industries in Otsuchi were fishing and, to a lesser extent, agriculture. On March 11, 2011, the Tohoku earthquake and tsunami swept through the city, destroying all but 30 of 650 fishing boats and completely wiping out the town's sea farm industry. In addition, 52% of the residential area in Otsuchi (431 ha) was submerged under water, and 1,284 lives were lost. The death toll reduced the population by nearly 10%. 3,359 houses were completely destroyed, and 713 houses were partially destroyed. 4,000 people who lost their homes were moved into temporary housing spread over 48 sites (Otsuchi General Policy Planning Division 2014).

The reconstruction plan includes town re-demarcation, collective relocation of residents, relocation of schools, public housing construction, and reconstruction of fishery facilities. The ground level in the Machikata residential area will also be raised by two meters to avoid being submerged (Otsuchi General Policy Planning Division 2014). The biggest disaster adaptation project, however, is a planned dike project for Japan's coastline. The 400-km chain of cement sea walls, up to five stories high, will cost 820 billion yen ($6.8 billion) to construct (Kurtenbach, 2015). Opponents argue that the dike will damage marine ecology and scenery, hinder fishery activities, and do little to protect residents who are supposed to relocate to higher ground in the event of a tsunami. In some areas (e.g. Iwanuma), lower sea walls existed (7-m) prior to Tohoku but the tsunami still swept up to 5 km inland. Survivors noted that stands of pine trees in the area were just as effective at slowing the water as the sea walls. Some residents are now proposing a "green wall" of mixed forest as an alternative (Kurtenbach, 2015).

3. Potential benefits of dike construction

The primary benefit of the dike is to prevent future damages from another Tohoku-like event in the future. There are three sources of uncertainty that make the problem challenging, however. First, damages from an event that has not yet occurred are unknown. We will use the 2011 Tohoku damages as a guideline. Second, we need to determine the likelihood that another Tohoku event occurs in the foreseeable future. Third, we need to determine how the expected damages from such an event are reduced as a result of dike construction.

3.1 Using realized 2011 damages to approximate expected damages

Assuming that past realized damages are a reasonable indicator of damages likely to be incurred in the event of a future disaster of similar magnitude, we begin by surveying damage estimates for the 2011 Tohoku event. Estimates for all of Japan range from 10 billion to nearly 600 billion USD (Table 1), depending on the model used and the types of losses included. An alternative is to estimate damage based on insurance claims, but in the case of Tohoku, it is estimated that less than 50% of damages were insured (Allman 2012). The remaining challenges are to determine the probability of another Tohoku-like event and to determine the damage reduction that can be attributed to the construction of the dike.

3.2 Likelihood of another Tohoku event

Forecasts of earthquake occurrence exist, but there is typically a high level of uncertainty. Seismic risk is defined by seismologists as the probability that an earthquake of a certain magnitude or greater strikes at least once in a region during a specified period. Seismic risk models may be time-independent or time-dependent. We will use the Poisson model, which assumes that occurrence is independent of time and independent of the past history of occurrences or non-occurrences. The framework used here is adapted from Wang (2006).

The probability of n earthquakes occurring during an exposure time of t years is

(1) $p_M(n,t,\tau) = \frac{e^{-t/\tau}(t/\tau)^n}{n!}$

where τ is the average recurrence interval of earthquakes equal to or greater than a specified magnitude (M). We can also think about it in terms of the average recurrence rate 1/τ. The probability that no earthquake will occur is

(2) $p_M(0,t,\tau) = e^{-t/\tau}$

Then, the probability of at least one M-level earthquake occurring within *t* years is

(3) $p_M(n \geq 1,t,\tau) = 1 - e^{-t/\tau}$

The corresponding probability density function is

(4) $f_M(t) = (1/\tau)e^{-t/\tau}$

The remaining unknown is the average recurrence rate 1/τ. The Headquarters for Earthquake Research Promotion (2015) estimates that the probability of an M8.6-9.0 earthquake occurring within the next 30 years off the eastern coast of Japan is 30%. Applying the formula above, for t=30 and p_M=0.3, we find that τ=84.

3.3 Present value of dike benefits

If we have an estimate for Otsuchi-specific damages (D) that would be realized in the event of an M-level earthquake, then the present value over the next T years of expected damages to Otsuchi from another Tohoku event is

(5) $\int_0^T e^{-rt}[D \cdot f_M(t)]dt$

However, the damage estimates summarized in Table 1 are for all of Japan (i.e. not just Otsuchi), and the sea wall would likely not reduce damage entirely to zero. Equation (5) would therefore largely overestimate the benefits (avoided damages) of the dike. To remedy this, we modify equation (5) to allow for a scale factor (α) and a damage reduction parameter (β):

(6) $\int_0^T e^{-rt}[D(\alpha,\beta)f_M(t)]dt$

Equation (6) says that the PV benefit of the dike is equal to the PV of total expected damages, adjusted to include only Otsuchi-specific damages and to incorporate the ability of the dike to reduce future damages. It is estimated that the tsunami flooded approximately 561 square kilometers across Japan. Recall that roughly 431 hectares or 4.31 sq km of Otsuchi was submerged in 2011. If damages from the tsunami and earthquake in 2011 are roughly proportional to the area submerged, then we can attribute 1% of total damage (4.31 ÷ 561) from the Tohoku event to Otsuchi, i.e. α=0.01. So for example, if D = 300 billion USD, expected damages for Otsuchi (assuming the dike is not rebuilt) are equal to αD, or 3 billion USD. As previously mentioned, the extent to which the dike will effectively reduce damage is highly uncertain. With that in mind, we allow the parameter β to vary from 0 to 1 for different levels of D in Figure 1.

For a given expected total damage D, PV benefits of the dike increases as the damage reduction parameter β increases. When β is relatively small, the absolute difference in PV benefits for different estimates of D is also small. As β increases, however, the absolute differences increase. For example, for β=0.2, i.e. 20% damage reduction, the PVB for D=500 is USD 203 million and the PVB for D=100 is USD 41 million, a difference of USD 162 million. For β=0.8, however, the difference is USD 650 million.

4 Potential costs of dike construction

The 400-km seawall project is expected to cost 6.8 billion USD in total (Kurtenbach, 2015). However, the cost for the dikes fronting Otsuchi will only be a fraction of that total. At the time of this writing, walls are planned for six locations in Otsuchi (Table 2). Seawall heights were calculated based on *Methods for Determining Design Tsunami Characteristics*,[1] a joint notice issued by the Ministry of Land, Infrastructure and Transport and Tourism and the Ministry of Agriculture, Forestry, and Fisheries. The height of 14.5 m, for example, was based on the 1896 Sanriku earthquake. Lower heights in other areas were requested as part of a larger plan to supplement the seawall with additional preventative measures. Bidding and construction has begun on some of the seawall projects (Table 3).

Total projected construction costs so far are estimated at JPY 7,454,407,329 or USD 61.8 million. Because this total does not include 5 of the 14 planned projects, we expect that total costs will be in the ballpark of USD 100 million. Although the seawalls will likely incur some maintenance costs over time, data is not yet available, so the present value cost calculations will only include the fixed construction costs.

5 Benefit-cost analysis of the dike project for Otsuchi

Because the construction costs are incurred in the initial period, the net present value is calculated by simply subtracting the USD 100 million initial cost from PV benefits for each scenario described in Figure 1. The result is a similar figure with the level curves shifted downward by the PV cost (Figure 2).

The breakeven value of β ranges from 0.1 for D=500 up to 0.5 for D=100. When the total expected damage is relatively low, the walls need to be more effective at reducing damage in order to generate a positive NPV for the project. Whereas in the high damage case (D=500), the walls need only reduce damage by 10% to ensure a non-negative NPV.

6 Concerns from the local community about non-monetized costs

While the calculation of the NPV includes only the damage reduction benefits and the construction costs of the dike, there are numerous other potential costs that should also be taken into consideration. Although we are unable to quantify all of these costs at this time, we discuss some of them in this section, using information gathered from a survey of the local community and preliminary data collected on nearshore ecological indicators.

6.1 Ecological losses

In July 2014, the project research team from the Research Institute for Humanity and Nature[2] conducted a field survey at 4 Japanese sites, one of which was Otsuchi. Information was collected on physical, chemical, and biological processes. Preliminary data suggests that more and larger fish are observed where submarine groundwater discharge (SGD) is higher. If the dike interferes with SGD, there will be implications both for the nearshore ecology and the fishing industry. Figure 3 compares temperature, salinity, and radon in Otsuchi Bay and nearby Funakoshi Bay. The higher temperature, lower salinity, and higher radon suggest that SGD is higher at Otsuchi Bay. Figure 4 compares fish counts and biomass. Otsuchi, the area with higher SGD, has more fish, a wider variety of species, and bigger fish. Thus if the dike impedes SGD to nearshore waters, there may be a negative impact on coastal fisheries. If the direct relationship between dike construction and SGD, as well as the relationship between SGD and the fishery

[1] http://www.mlit.go.jp/common/000149774.pdf
[2] http://www.chikyu.ac.jp/rihn_e/project/R-08.html#

were known, one could estimate the effect of dike construction on the fishing industry. The results could then be included with the the fixed construction costs in the benefit-cost analysis.

In addition to expected impacts to the fishing industry due to ecological impacts of a potential reduction in SGD, results from an interview of Otsuchi residents suggest that other ecological impacts are nontrivial. By raising homes two meters to protect against inundation, approximately 200 groundwater springs will be lost. A “sunken garden” has been proposed as a mitigation strategy, which would be a community groundwater resource. The dike would also affect the habitat for the nationally protected Itoyo (three-spined stickleback), so a park/pond has been proposed as a mitigation strategy. The economic value of threatened, endangered, or rare species such as the Itoyo can be substantial. For example, after surveying a number of valuation studies, Richard and Loomis (2009) find that average annual willingness to pay per household for the protection of fish species ranges from $12 for squawfish up to $81 for salmon/steelhead.

6.2 Aesthetic concerns of lost view

Anecdotal evidence suggests that residents are concerned that the dike will block beach access and the view, both of which are also valuable to the tourism industry. For example, one beach hotel opted to not have a dike placed in front of it. In Namiita, residents are against the reconstruction of the seawall entirely because they want to preserve the natural scenery, while in Akahama, the resident consensus was to keep the seawall at its previous level and move the residential area to higher ground to preserve the scenic benefits (RINC 2015).

6.3 Incorporating non-monetized costs into the CBA

Although we cannot assign an exact dollar value directly to the costs discussed in section 6, they can be incorporated into the CBA indirectly. In particular, we can say that for a given set of parameter values, the project should be undertaken only if the calculated PV net benefits are not only positive, but also exceed the perceived costs that are non-monetized. Otherwise, costs exceed benefits in present value terms, and the residents are better off without the dike. For example, the NPV for D=300 and $\beta=0.25$ is USD 53 million. If we expect that the dike will impose a cost of more than USD 53 million on the tourism and fishing industries in present value terms (even if we cannot calculate the exact value), then the dike should not be built.

7 Dike alternative

Observers say that stands of pine trees worked just as well as the seawall at slowing the water during the 2011 Tohoku event. It costs between USD 970-1,550 (adjusted for inflation) to establish a one-hectare stand of pine trees in the Western Gulf area of the United States (Taylor et al. 2006). The costs will likely be slightly different in Japan, so we conservatively assign a per-hectare cost of USD 2,000. Assuming that one tenth of the proposed 400-km sea wall project would front Otsuchi, replacing the dike with a natural wall of pine trees would require roughly 800 ha of pine (two rows of forty 100-m x 100-m stands), and the total cost would be USD 1.6 million. If the pine trees are in fact as effective as the seawall, the potential cost savings are substantial; recall that the expected construction cost was estimated at USD 100 million, orders of magnitude higher than the PV cost of the pine trees.

8 Discussion

We find that the net present value of the planned seawall in Otsuchi is positive when the wall is relatively effective at reducing damage and total expected damages from another Tohoku-level event are high. The breakeven point will increase when we consider other potential non-monetized costs. Anecdotal evidence suggests that the costs could potentially be reduced while maintaining a similar level of benefits by using pine trees as a natural sea wall. If this is indeed the case, then social welfare in Otsuchi would likely be higher if the national government developed disaster adaptation strategies in cooperation with local residents and other stakeholders, particularly in light of the 2011 ordinance that called for disaster recovery in cooperation with local citizens. However, the dike project would provide construction jobs over a longer period of time at the national level (there is no guarantee that the jobs would be made available to residents of Otsuchi), which suggests that the number and groups of beneficiaries can change depending on the scale being considered. Allowing for hybrid methods of governance such as a public-private partnership would bring into the discussion alternative adaptation strategies and highlight the importance of understanding who the beneficiaries are and who is shouldering the costs.

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Table 1. Estimated damages for 2011 Tohoku earthquake and tsunami (all of Japan)

Source	**Description**	**Damage (USD)**
USGS (2011)	Estimated losses due to structural damage only (resistant to vulnerable structures)	10-100 billion[1]
Daniell et al. (2011)	Includes indirect losses (43% of the total) such as interruption to businesses	595 billion
Japan Ministry of Economy, Trade and Industry (2011)	Macroeconomic impact includes damage to all stocks (social capital, housing, private plants and equipment)	130-203 billion
Allman (2012)	Total economic losses	210 billion
Kazama and Noda (2012)	Estimated damage to buildings, lifeline facilities, social infrastructure facilities, agriculture, forestry, and fisheries production	80-209 billion[2]

[1]The range is a result of uncertainty stemming from data limitations and the fact that potential damage varies across and within structure types.

[2]The range is due to different assumptions about rates of damage to buildings.

Table 2. Seawall heights and configurations in Otsuchi

Bay	District	Structure	Restored height	Alignment
Otsuchi Bay	Machikata	Seawall/floodgate	14.5 m	Current
	Komakura	Seawall	6.4 m	Current
	Ando	Seawall	14.5 m	Change
	Akahama	Seawall	6.4 m	Current
Funakoshi Bay	Kirikiri	Seawall	12.8 m	Current
	Namiita	Seawall/ forests	4.5 m	Current

Source: RINC (2015)

Table 3. Progress of Otsuchi seawall projects

District	Project	Bid amount (budget in JPY)	Estimated cost (JPY)*	Remarks**
Machikata	Name TBA	TBA	266,885,959	Three planned seawalls totaling 552.7 m in length
Komakura	Otsuchi Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 556 Shiroishi District Seawall)	TBA		Bidding scheduled for FY2015
Ando	Otsuchi Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 556 Ando District Seawall 1)	352,500,000		730 m in length
	Otsuchi Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 556 Ando District Seawall 2)	TBA	72,431,507	Bidding scheduled for FY2015; 150 m in length
	Otsuchi Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 556 Ando District Seawall 3)	TBA		Bidding scheduled for FY2015
Akahama	Otsuchi Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 556 Akahama District Seawall)	TBA	313,869,863	Bidding scheduled for FY2015; 650 m in length
Kirikiri	Kirikiri Fishing Port and Coastal	389,000,000		

	Disaster Recovery Construction Project (2011 Disaster Pref. No. 555 Seawall 1)		
	Kirikiri Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 555 Seawall 2)	TBA	Bidding scheduled for FY2015
	Kirikiri Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 555 Seawall 3)	745,050,000	
	Kirikiri Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 555 Seawall 4)	450,970,000	
	Kirikiri Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 555 Seawall 5)	TBA	Further investigation required
	Kirikiri Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 555 Seawall 6)	TBA	Bidding scheduled for FY2015
Namiita	Funakoshi Fishing Port and Coastal Disaster Recovery Construction Project (2011 Disaster Pref. No. 554 Seawall 1)	1,318,700,000	
	Funakoshi Fishing Port and Coastal	3,545,000,000	Combined with the former

Disaster Recovery Construction Project (2011 Disaster Pref. No. 554 Seawall 2)	Funakoshi Minami District Coastal Disaster Recovery Construction Project (2011 Disaster No. 599) 2

*Based on the per-meter cost of 482,877 JPY budgeted for the Ando District Seawall 1.

**Seawall lengths estimated using data from the Coastal Promotion Bureau of Iwate Prefecture Government (2015)

Primary Source: RINC (2015)

Figure 1. PV dike benefits (α=0.01, r=0.03)

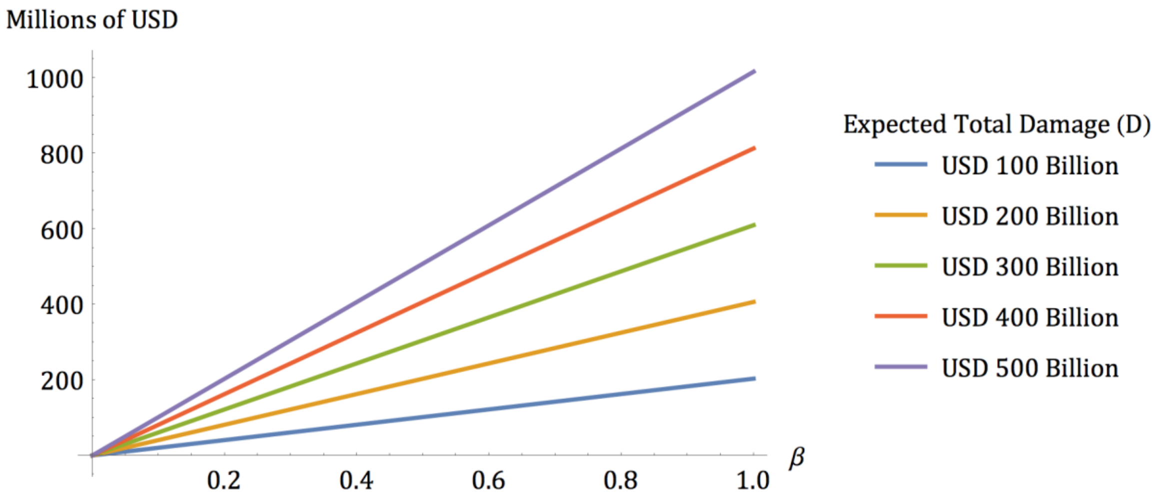


Figure 2. PV dike net benefits (α=0.01, r=0.03)

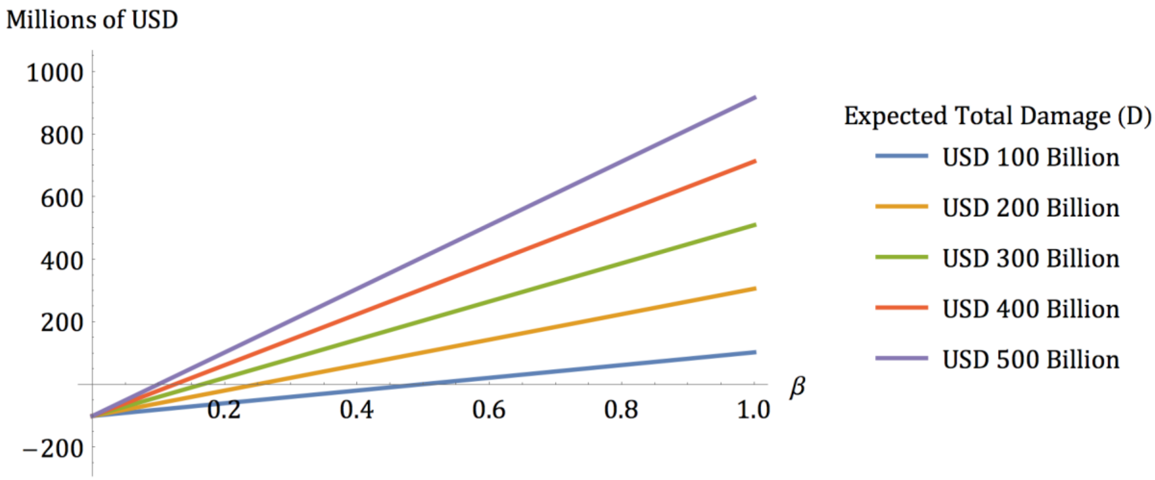
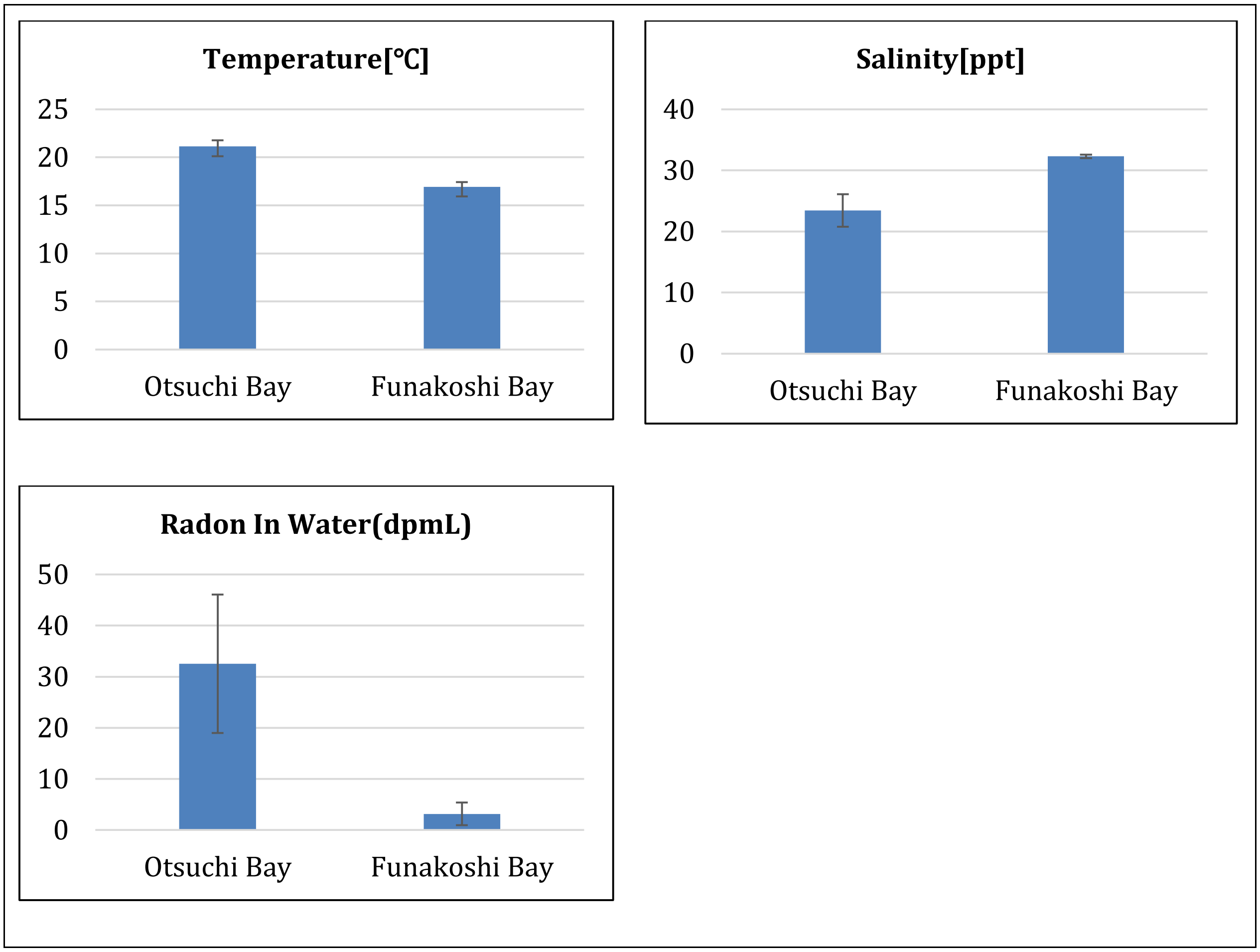
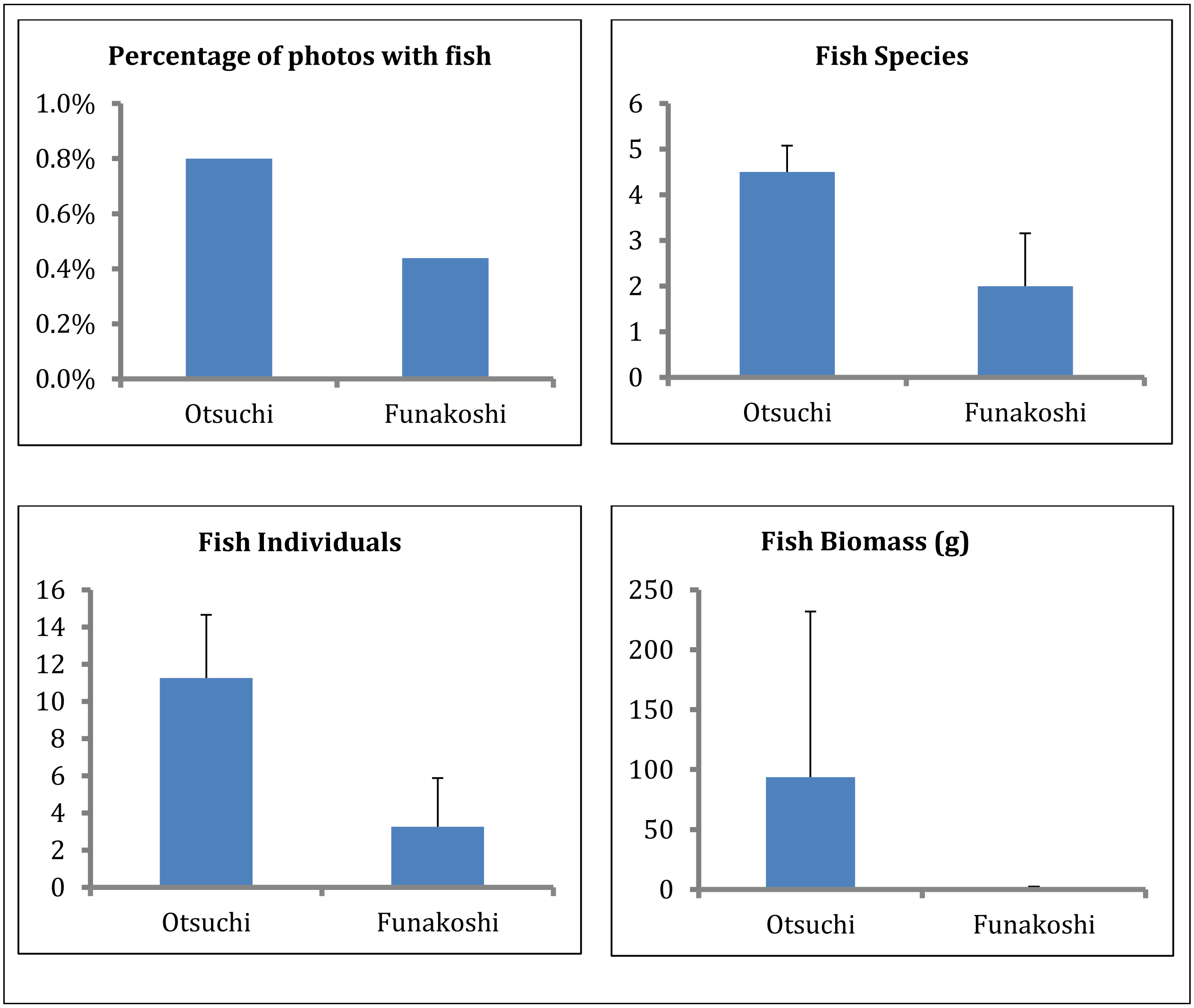


Figure 3. Temperature, salinity, and radon in Otsuchi and Funakoshi



Source: Honda et al. (2014)

Figure 4. Fish counts and biomass in Otsuchi and Funakoshi



Source: Honda et al. (2014)