The Economics of Nuclear Decontamination: Assessing Policy Options for the Management of Land Around Fukushima Dai-Ichi.

by

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Abstract:

Economic analysis of nuclear accidents is comparatively rate. I provide an overview of methods used to assess the economic impact of nuclear accidents, a summary of attempts to date to estimate the costs and policy responses to accidents. In addition I create a simple framework for assessing the merits of different decontamination strategies.

Keywords: Nuclear accident, environmental valuation, radiation, economics, Fukushima Dai Ichi, Chernobyl, Windscale, 原子力, 原子力発電

JEL Codes: D61, Q51, Q53

1 Introduction.

For large-scale nuclear accidents such as Chernobyl or Fukushima a large part of the economic cost arises from the on-going evacuation of contaminated land and cities, together with the abandonment and destruction of capital and infrastructure. Lost assets typically include physical assets (e.g. the reactor, machinery, housing abandoned or destroyed), natural assets such as forests and fisheries as well as human capital in the form of increased morbidity and in some cases, increased mortality. Large-scale accidents are significant shocks and can of course have spill over consequences throughout the economy, through demand changes and the disruption of the supply chain. In addition a major unforeseen event may be followed by a period of increased uncertainty which itself affects economic activity (Bloom, 2009). In this context, decontamination is one of a number of possible strategies that can be employed to mitigate the costs of an accident. Prior to Fukushima it has not been used on a significant scale.

For instance, around Chernobyl, management has been by containment, evacuation, abandonment and exclusion from the affected zone (United Nations, 2002). Attempts at decontamination have been limited (WHO 2005) although some partial attempts at decontamination have taken place in neighbouring countries (Tveten et al, 1998 , Strand et al, 1990). However, in the case of Fukushima the national government has made decontamination a priority and is devoting several billions of dollars (US) each year to the exercise (MOF, 2011).

In this paper I create a basic model to assess decontamination and resettlement strategies for land affected by the release of radioactive materials. In particular, I focus on the merits of delaying decontamination and resettlement of evacuated areas.[1] While there are other important aspects of nuclear accidents that await a policy analysis, this particular issue seems especially pertinent given the firm commitment made by the Japanese government to the quick, but potentially costly, clean-up of the regions that neighbour Fukushima dai-ichi nuclear power plant (MOE, 2011a). Delayed intervention might seem a counterintuitive policy, because deferring resettlement means also postponing the benefits that come once land and houses etc. are used again. However, because the costs of clean-up are increasing in the level of contamination, delay also reduces the costs of intervention. Of course there are many ongoing costs associated with evacuation, but if radioactive decay is relatively rapid and site cleaning is costly, waiting can be optimal. The argument is illustrated by Figure 1 which is based on the numbers used later in the paper. In this figure the present value of resettlement declines with time, but radioactive decay means that the present value of costs falls more quickly than benefits and, as a result, there is an optimum delay before resettlement of approximately 8.75 years.

Figure 1. Costs and Benefits as a function of Delay Time. Source: own calculations

Although it has not received academic analysis, this possibility of delayed intervention seems an important margin for policy decisions, especially given the simultaneous need to rebuild other parts of Tohoku affected by the 2011 earthquake and tsunami. One major lesson of the paper is that while the exact period of optimal delay varies according to parameter values, it is

[1] I am not here concerned with the decommissioning of the plant itself, but with policy towards the surrounding towns and villages, many of which are currently evacuated.

almost always optimal to take advantage of the fact that radiation levels decay naturally and quite rapidly in the case of Caesium 134. This result seems to be robust, but it should not mask the fact that there is considerable uncertainty over the value of critical variables.

A secondary aim of the paper is methodological: to present an analysis of policy options within a standard cost benefit analysis framework. In the sixty or so years in which nuclear power has been used to generate electricity, there have only been 2 events that merit a '7' on the International Atomic Energy Authority's (IAEA) event scale for accidents. There is relatively little work done on assessing policy options in their wake. Moreover, much of that work (e.g. United Nations, 2002, Chernobyl Forum, 2006 or WHO 2005) is inappropriate at least in terms of its economic methodology, because it often omits important costs, measures benefits by costs and treats transfers inconsistently.

2 Background.

Nearly all of the current dose exposure around Fukushima is by isotopes of Caesium (134 and 137) which were originally deposited in the ratio 1:1. The former has a 30.17 year half-life whereas Caesium-134 has a half life of 2.06 years. Because of the short half-life of Caesium-134, exposure falls rapidly (see Figure 2 below). After 10 years or so, Caesium 137 becomes the dominant isotope and as a result the average rate of decay falls.

Figure 2. Reduction of the relative external exposure rate subsequent to deposition of Cs-134 and 137 (original ratio = 1:1) due to radioactive decay. Source: IAEA 2011

The pattern of restrictions and evacuations on human activity is shown in Figure 3. The Evacuation prepared area notice was removed in September 2011, but evacuation and restricted access was still in force as of April 2012 and for the foreseeable future, with approximately 90,000 people moved out of the area (some families in adjacent areas have also relocated). There are approximately 500 km^2 where radiation dose levels are above 20 mSv per year (mSv/a) and about 1300 km^2 where levels are between 5 mSv/a and 20 mSv/a (IAEA 2011). As Yoshida and Kanda 2012 note there are a number of other areas of large scale deposition of radionuclides south and west of Fukushima, particularly in the adjacent Gunma and Tochigi prefectures.

Figure 3. Restrictions around Fukushima in 2011: Source: IAEA

From an early stage the Japanese government has committed to large-scale decontamination of the areas surrounding Fukushima.[2,] In addition, citizen's groups and volunteers have also been active in cleaning, often without prior approval or guidance by local government (IAEA 2011). The currently declared aim of the Japanese government is to reduce quickly the theoretical exposure in affected areas to 20 mSv per year (MOE, 2011a). Meanwhile long-term exposure should be reduced to 1 mSv per year.[3] Within this broad framework, special focus has been placed on the exposure of children where through school and school yard decontamination, the aim is to reduce the exposure to an effective dose of 1 mSv per year during the time children are at school.[4] Plans for restoring economic activity and residence in the currently-evacuated areas are not finalised, but there is a suggestion that at some point below 20mSv some re-settlement will occur, albeit with ongoing restrictions on activity (MOE, 2011a). As summarized in Figure 4, the plan divides responsibilities between the national ministries and local governments. The former handle evacuated and restricted areas with exposure levels above 20mSv while the prefectures (and local municipalities) supervise decontamination efforts for areas where exposure is below 20mSv. In the third supplementary budget of 2011, 249bn Yen (approx 2.45bn Euros) was set aside for 2012 for decontamination efforts for 2012 (MOF, 2011).

A notable feature of the current plan, criticized by the IAEA, (IAEA, 2011), is the aim to remove large volumes of low-radiation topsoil and waste and to store them in secure facilities for an extended period. If zones with contamination levels above 5mSv are cleaned up the estimated volumes range from 20.8m m^3 to 28.8m m^3 – enough to cover a 1 km square 20.8 to 28.8 metres deep (IAEA, 2011, Table 1).

3 The value of delaying decontamination.

In the face of contaminated land, there are two basic dimensions to the policy options faced by decision-makers. One dimension represents the period of relocation for affected residents and

[2] On 26 August 2011, The Parliament (Diet) of Japan approved the *"Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District – Off the Pacific Ocean Earthquake that Occurred on March 11, 2011".* This sets out the current legal framework.

[3] These target figures are for the excess over any pre-existing natural exposure and medical exposure.

4 What the ICRP states is that, "The reference level for the optimisation of protection of people living in contaminated areas should be selected in the lower part of the 1–20 mSv/year band… Past experience has demonstrated that a typical value used for constraining the optimisation process in long-term post-accident situations is 1 mSv/year." P. 11. in ICRP, 2009.

business. At the extreme of this spectrum there is permanent relocation outside the affected zone. At the other extreme there is no relocation even of the temporary kind. The major costs of evacuation include the flow of lost benefits from temporarily abandoned assets such as houses, roads, farms and schools. In addition there may be costs of rehousing relocated individuals and individuals moved from familiar environments may face worse health. Although some work emphasizes the out-of-pocket expenses of relocation, (e.g. IAEA 1994) in fact, for periods of time beyond a few months it is the opportunity costs that dominate. Against the tally of costs, relocated individuals receive benefits from their temporary accommodation and of course from the reduction in health risk associated with lower radioactive exposure.

The second policy dimension represents the intensity of decontamination strategy. The extremes of this dimension are: do nothing and restore radioactive exposure to the pre-release level. At the risk of some simplification, I summarize the choice variables as T, the time for resettlement after evacuation and s, the target level of dose exposure below which clean-up efforts cease. In modelling the policy options there are obviously different approaches. One option is to fully endogenous the benefits associated with s and to choose both the optimal long-term value for s and the approach path. It is questionable whether this is realistic given the policy context in Japan. Major decisions on the management of radioactivity tend to be set with regard to pre-existing international norms on safe levels of exposure (e.g. IAEA, 1994 and Figure 4). Moreover, policy tends to be discrete in nature. For instance, individuals are either evacuated or not from a contaminated zone. So, for the most part I take it that target levels of radiation exposure for resettlement and long-term exposure are given and this frames the policy options. However, I do also consider briefly the optimal level for s.

Figure 4. Remediation plans around Fukushima (adapted from Figure 2, Moriya 2011).

There are therefore two cases that are considered in detail:

Case 1. evacuation followed by re-use. Benefits flow from the time at which exposure reaches acceptable levels, resettlement occurs and assets are re-used. Costs are an increasing function of the exposure to be removed. This is the case that is most relevant for currently evacuated areas.

Case 2. in-situ clean-up with stochastic benefits. Costs are an increasing function of the exposure to be removed. Benefits flow from clean up time and are proportional to amount of exposure removed. This is the case that is most relevant for areas that are not currently evacuated.

To assess intervention options, there is a simple pre-existing framework set out by the IAEA (e.g. IAEA 1994) that focuses primarily on the relocation decision or on in situ clean-up (Hedemann-Jensen, 1999 and Hedemann-Jensen 2004). The IAEA's approach to the benefits of reducing radiation exposure is based on the associated, stochastic health benefits and uses a simple human capital method. The basic model is one in which at the level of the individual, the risks of death and increased morbidity are linear in exposure (IAEA, 1994) with no lower threshold. A similar model is presented in Dreicer et al, 1995. The gain, B, from a reduction in exposure of Δ (measured in 'man Sieverts' or manSv) is then given by formulae,

$$B = \Delta v (1 + \beta + \delta) p \eta$$

Where p is the probability coefficient for fatal cancer induced by radiation ($per^{-1}Sv^{-1}$), β is the relative weight put on a non-fatal cancer relative to a fatal cancer, δ is the relative weight put on hereditary consequences relative to a fatal cancer and η is the mean number of life years lost to a fatal cancer. In the IAEA model, it is taken that $\eta=13$, while $p = 0.05$, $\beta=0.01$ and $\delta=0.013$, meaning that the formula is taken to be 'approximately' $B = \Delta v$. The coefficient v (\$/life year) is the monetary value of a statistical life year (VSLY).[5] In the model there is no explicit treatment of the gains from delay, but the benefits from particular interventions (i.e. values of Δ) can be compared to the costs.

While this framework might be reasonable for in-situ reductions in exposure it is not applicable when the affected area is evacuated. In such a case, the gains from decontamination arise through any associated reduction of the period of costly evacuation and the consequential return of benefits for individuals living in their own homes, businesses and farms, using local schools and infrastructure etc. The original model (IAEA 1994) provides some broad estimates of the costs of evacuation and resettlement for different time periods of evacuation. However it does not attempt to give a formal treatment of the pros and cons of different policies, including delayed decontamination.

The IAEA model is therefore incomplete. To take it further, I consider a unit area of contaminated land where the excess radiation exposure is initially x, decreasing exponentially

[5] The model is for stochastic rather than what the IAEA terms 'deterministic effects', meaning the formula is based on the underlying notion that individual doses are less than 0.1 $Sv.h^{-1}$ and total less than 0.2Sv per person. A fuller version of the model includes the costs of elevated risks for the clean-up workers, but quantitatively these are only a very small fraction of total costs.

at the rate of a, so that at time t, in the absence of any decontamination efforts, the excess exposure is $y = xe^{-at}$. The target level is s, which is greater than or equal to zero. In case 1, the target is the level of exposure at which resettlement is allowed. In case 2, s is the level of exposure at which decontamination efforts cease.

The cost of cleaning (e.g. by removal and safe storage of soil) an excess dose of y to a level of s is c(y,s). The evidence on the functional form of c is scanty (Brown et al, 1996, Thiessen et al, 2009). However, in the wake of the Fukushima accident, the Japanese government has organized a number of decontamination pilot projects in different locations and environments (Japan Atomic Energy Agency, 2012). The evidence from these sites is consistent with a simple linear model (see Figure 5) where the ratio of before and after excess dose is a constant which I label μ. In other words, starting with a level y, after 1 decontamination exercise, the remaining dose is yμ and after n attempts the remaining excess dose is, $y\mu^n$. Then, to achieve a target of s, $n = \ln(y/s)/\ln(1/\mu)$. If each decontamination exercise costs c, the cost function is $c(y,s)=c\ln(y/s)/\ln(1/\mu)$, with $c > 0$. [6]

Figure 5. Before and After plot from Fukushima pilot decontamination projects: Source: own calculations from JAEA, 2012

Define the net flow of benefits from resettled assets as b(t) per unit area and the discount rate as r. The functional form of b depends on the case.

<u>Case 1.</u> For the case of evacuation, b(t) has the following functional form:

$$b(t) = \begin{cases} 0 & t < T \\ b_0 - b_1 s e^{-a(t-T)} & t \geq T \end{cases}$$

This equation can be read as follows: prior to resettlement at time T, there are no benefits from decontamination. After T, the first term in the equation represents the net flow of benefits from the re-use of the assets,[7] but any return to a partially contaminated site is associated with some elevated risks and this gives the second, negative term in the benefit equation. In case 1, since there are no benefits from decontamination efforts prior to re-settlement then all decontamination will occur as close to T as is feasible. Thus, the problem is reduced to finding the date at which the decontamination meets the target and land becomes

[6] Since fractional clean-ups are feasible (e.g. by cleaning less than 100% of an area) I take n to be continuous in what follows.

[7] For simplicity I keep b_0 as constant, but over extended periods, assets may depreciate and this may lower the benefits of resettlement.

settled again.

So, the problem is to choose T to maximize the welfare function, W, which is defined in a conventional manner as the difference between the net present values of benefits and costs:

$$W = -c\frac{\ln(y/s)}{\ln(1/\mu)}e^{-rT} + \int_T^{\infty}\left(b_0 - b_1 s e^{-a(t-T)}\right)e^{-rt}dt.$$

subject to $y = xe^{-aT}$. Simplifying, the equation for W is then,

$$W = -c\frac{\left(\ln(x/s) - aT\right)}{\ln(1/\mu)}e^{-rT} + \frac{b_0}{r}e^{-rT} - \frac{b_1 s}{a+r}e^{-rT}$$

Unless $s = xe^{-aT}$ $T \geq \frac{1}{a}\ln\left(\frac{x}{s}\right)$ $T = \frac{1}{a}\ln\left(\frac{x}{s}\right)$ in which case no clean-up is required to meet the target and so $W = \frac{b_0}{r}e^{-rT} - \frac{b_1 s}{a+r}e^{-rT}$. For, $T \leq \frac{1}{a}\ln\left(\frac{x}{s}\right)$ the first order condition is,

$$\frac{dW}{dT} = \frac{ac}{\ln(1/\mu)}e^{-rT} + \left(\frac{\ln(x/s) - aT}{\ln(1/\mu)}\right)rce^{-rT} - b_0 e^{-rT} + \frac{rsb_1}{a+r}e^{-rT} = 0. \qquad (1)$$

Note that $d^2W/dT^2 < 0$ for $T \geq 0$, so that there is a unique maximum. Solving,

$$T = \frac{1}{r} + \frac{\ln(x/s)}{a} + \ln(1/\mu)\left(\frac{-b_0}{acr} + \frac{sb_1}{ac(a+r)}\right)$$

This interior solution holds unless, $\left.\frac{dW}{dT}\right|_{T=0} \leq 0$, in which case it is optimal to clean up and resettle at time 0. Alternatively, if $1 + \ln(1/\mu)\left(\frac{-b_0}{ac} + \frac{rsb_1}{ac(a+r)}\right) > 0$, then it is optimal not to actively clean the land at any time, but to delay resettlement until the time when radiation naturally falls to s. Thus there are three sub-cases: (i) immediate restoration; (ii) delayed clean-up and (iii) let nature take its course (i.e. no active clean-up).

It can be shown (see appendix) that the optimal delay rises with the discount rate, r, with the benefits from reduced exposure, with the unit cost of cleaning and with μ. It is also increasing with the initial level of exposure and decreasing in the benefits from resettlement. The impact of changes in a or s are ambiguous. For a, an increase in the rate of natural decay means waiting leads to lower costs of clean-up. This factor pushes up T. On the other hand, higher a means that the time at which the site reaches a target level of exposure is shortened and this also means that it is more advantageous to begin decontamination sooner rather than later. For s, a higher value means that the gains from resettlement are lower, but at the same time it is easier to meet the target for resettlement.

Case 2. For case 2, the immediate benefits from intervention are proportional to the reduction in exposure achieved by the clean-up operation. If the target is s, then starting from an initial rate of exposure of x, delaying a clean-up until time T means that W is,

$$W = b_1 \int_T^{\infty} e^{-rt}(xe^{-at} - se^{-a(t-T)})dt - c\frac{\left(\ln\left(\frac{x}{s}\right) - aT\right)}{\ln\left(\frac{1}{\mu}\right)}e^{-rT} = e^{-rT}\left(-c\frac{(\ln(x/s) - aT)}{\ln(1/\mu)} + \frac{b_1(xe^{-aT} - s)}{r+a}\right)$$

Optimal delay is found by maximizing this function with respect to T and the solution can be found in a similar manner to case 1. The first order condition is,

$$\frac{ac}{\ln(1/\mu)} + \left(\frac{\ln(x/s) - aT}{\ln(1/\mu)}\right)rc - r\left(\frac{b_1(xe^{-aT} - s)}{a+r}\right) - \frac{axb_1}{a+r}e^{-aT} = 0 \qquad (2)$$

As in the previous case, there may be corner solutions, meaning that no delay or no active clean-up can be optimal.[8]

Before proceeding to simulation, there is a significant adjustment that needs to be made to the model. As noted above, in the case of Fukushima there are two main sources of ongoing radiation exposure: Caesium 134 and 147. Since they have different half-lives, dose at time t is a weighted average of the dose from the remaining quantities of the two isotopes as in Figure

[8] In the event that the target for radiation reduction can also be freely chosen by the planning authority, the condition for the optimal number of clean-ups is, $y\mu^n = c(a+r)/(b_1 \ln(1/\mu))$ where y is the exposure at the moment the decontamination commences. If $c \geq \ln(1/\mu)\, yb_1/(r+a)$ then n=0. In other words if the costs per clean-up are sufficiently high or the gains in reduced exposure are sufficiently low, no clean-up is optimal. Otherwise, the final level of exposure is independent of the initial level.

2. I therefore replace xe^{-at} by $xf(t,\alpha)$ where f is a weighted average of the doses from the component nuclides and α is a shift parameter. Ultimately, in the derivation of the optimal delay the basic analysis is the same: there are three possible sub-cases to consider and all the comparative statics for T are unambiguous except for α and s.

3.1 Parameter values.

Finding reasonable values for some of the parameters is not always straightforward given the paucity of data on previous incidents and attempts at clean-up, so it is important to stress once again the uncertainty surrounding some of the figures in this section. The function f = (0.74exp(-0.3356αt)) + 0.26exp(-0.0230αt) with α=1 corresponds to the IAEA, 2011, exposure decay curve shown in Figure 2 and provides a benchmark figure for this parameter. With this function, the first order equation for welfare maximization (1) becomes,

$$\frac{x\left(0.74(0.3356\alpha + r)e^{-(0.3356\alpha)T} + 0.26(0.023\alpha + r)e^{-(0.023\alpha)T}\right)}{\ln(1/\mu)} + \left(\frac{\ln(x/s)}{\ln(1/\mu)}\right)r - \frac{b_0}{c} + \frac{rsb_1}{c}\left(\frac{0.74}{0.3356\alpha + r} + \frac{0.26}{0.023\alpha + r}\right) = 0. \tag{3}$$

In practice α might differ from 1 according to the terrain, weather etc, but typically the range of variation will be small and the results reported below are not sensitive to small changes in it. For that reason we do not report sensitivity analysis for α below.

For r, given Japanese interest rates, the range of 0.01-0.10 per annum is reasonable with a central figure of 0.04.

For s and x a number of combinations are possible. As noted above, the ultimate target level for radiation exposure is 1mSv per year. However, it is likely that the Japanese government will allow access to the excluded zone and resettlement before the eventual target of 1mSv per year is reached. At the same time, in many parts of the evacuated zone, current exposure levels are well above 20mSv per year with annualised figures exceeding several hundred mSv per annum at some sites (JAEA, 2012). Thus for case 1, setting x = 20-100 and s = 1-20 provides a reasonable range with x = 50 and s = 5 as a benchmark combinations. Outside the excluded zone, exposure is already typically below 20mSv, yet intensive decontamination is also planned for these areas (Moritani, 2011). So for case 2, I take a benchmark combination of x=20 and s=1 in keeping with the current policy framework.

Estimates for μ are based on figures produced by the recent demonstration projects at 78 sites in 15 towns (JAEA, 2012). Fifteen sites are control sites with no active decontamination efforts. The other 63 sites represent a variety of asset types including roads, farmland, houses and large buildings. At the majority of sites exposure was under 100 mSv per annum before intervention but there are 9 sites with levels above 100mSv per annum ranging up to 1198mSv per annum. I use the control site figures to obtain a net effect from active decontamination. Regressing the after decontamination exposure on the level before decontamination, I cannot reject the hypothesis (at the 95% level) of a zero intercept. Also, I cannot reject the hypothesis of no statistically significant relationship between asset type and rate of reduction. The coefficient on the prior level is 0.559 (with a 95% confidence interval of 0.36-0.76 based on clustering errors by asset type). This means for instance that a typical clean-up removes about 44.1% of an original exposure level. The estimation is potentially sensitive to the inclusion of the small number of high dose sites. Excluding sites with annual dose above 100mSv produces a coefficient of 0.61. Not adjusting for the reduction in exposure levels at the control sites changes the coefficient to 0.52. I what follows I set the benchmark value of μ=0.559 and use the 95% confidence intervals to guide sensitivity analysis.

Estimating c with precision is a difficult issue. Although a decontamination budget has been set by the Japanese government for 2012 and 2013 there are no associated estimates of costs per hectare at the national level. Indeed, the largest part of the budget for 2012 is on demonstration projects (MOF, 2011). The cost per hectare is also likely to vary with terrain type and land use. One historical source of data is Hedemann-Johnson, 2003, which conducts simulations of clean-up costs for urban and semi-urban areas using some earlier cost figures for the UK set out in Brown et al, 1996 converted into GNP per capita units. However, these figures are a fraction (about 1/10) of the current indicative prices set by Fukushima prefecture in its invitation to tender documents (Fukushima, 2011) and the values of the winning bids for model clean-up operations. For this reason I centre our figures on the Fukushima data, limited though it is. The Fukushima tender documents suggest a cost of approximately 9 million Japanese yen per hectare for farmland clean-up, though the figures do not include long term storage costs for any material removed from the site. As such they may be an underestimate.[9] The same documents provide a figure of approximately 700,000 Yen for cleaning up a residence which

[9] The guide prices may include rents, but recent figures for the demonstration figures (JAEA 2012) are however in line with the quotes.

occupies a land area of 400m^2. In February 2012 the first major contracts were implemented for model clean-up operations. In these awards, for instance, Mitsui Sumitomo Corporation won a contract to decontaminate 267 houses for Fukushima prefecture at a price of 200m Yen (about 1.95m Euros) or 795,000 per house.[10] Since the prefecture is responsible for decontaminating areas with exposure levels below 20mSv per year, then the costs of clean-up for more contaminated sites may be significantly higher. For instance, in the first round of contracts for areas under national government control, the construction company Taisei Ltd successfully bid to clean up 62 hectares at a price of approximately 51.6m Yen per hectare, which is well above the 9m yen guide price quoted by the Fukushima prefecture prospectus.

Although there is information on decontamination costs for specific items, an important question concerns how they should be aggregated, given that individuals typically divide their day between different locales, including home, roads, work etc. Two strategies are employed. The first is to use the individual figures for homes, farmland etc. and suppose the individual does not use other assets. The second is to calculate an approximate weighted average. In this calculation, prefecture level figures on population, households and land use are assumed to be representative of the affected areas.[11] The formula I use for the unit cost of clean up is,

$$C = \frac{1}{A_F}\left(R_F c_r + A_f c_{fa} + H_F c_H + \gamma A_W c_w + U_F c_u\right)$$

Here, A_F is the total area of Fukushima, R_F is kilometres of paved roads in the prefecture, A_f is the area of farmed land, H_F is the number of households, A_w is the area of woodland and U_F is the area of urban land. Cost per unit are, c_r for roads, c_{fa} for farmland, c_H for housing, c_w for woodland and c_u for non-housing urban sites. The symbol γ represents the fraction of woodland that is actively cleaned (implicitly, for other assets $\gamma=1$). The cost C is therefore in units of Yen/hectare. Alternatively A_F could be replaced by H_F in the denominator to get a figure per household.

For c_w, Fukushima 2011, provides guide prices of 60,000 Yen per hectare for removing leaves and loose material from contaminated areas adjacent to housing based on $\gamma=0.1$. I set $\gamma=0.1$ on

[10] According to the Asahi Shinbun newspaper, a number of the contract winners bid below cost in order to acquire experience and establish a track record for decontamination. See http://www.asahi.com/business/topics/economy/TKY201201310154.html (in Japanese).

[11] The affected zones do not include the largest urban areas for Fukushima or the highest upland regions. As such, using prefecture level estimates will tend to overestimate the urban clean-up costs and underestimate farmland costs.

the basis that this is the figure used in the tender documents and represents woodland adjacent to built-up areas. I include estimates for non-housing buildings using the same source. For typical roads, the quoted figure is approximately 240,000 Yen per kilometre though it is worth noting that some test sites reported in JAEA 2012 produce example estimates that are several times this. I then calculate an average cost at the household or hectare level. Using the Fukushima invitation to tender figures this gives a range of 1.38m to 3.49m Yen per household (or 0.75 to 1.89m Yen per hectare) depending largely on whether a high or low figure for farmland clean up is used. I use the mean of these figures (2.43m Yen per household or 1.32m Yen per hectare) and use the upper and lower figures for sensitivity analysis. Using the actual winning bid figures for the Taisei bid for instance would push up the cost per household to 14.2m Yen – several times annual income per capita.

What are appropriate values for benefits, b_0 and b_1? Again this is uncertain and likely to depend on post-resettlement land use, whether activities (e.g. outdoor play by children) are restricted, but also the costs of supplying alternative assets during the period of evacuation and the associated benefits from these assets. My approach here is to suppose for the purposes of the exercise that b_0 is well-approximated by the prior flow of benefits from the evacuated areas. This means that the evacuation costs cancel out the benefits from assets temporarily supplied during the evacuation period. In the case where resettlement leads to the full restoration of benefits, some figures for b_0 can then be estimated from the flow of farm income, and from house prices and rents. Now, I do not have direct estimates of value derived from nearby public buildings and infrastructure such as roads or for other types of land use such as woodlands although at least in theory, the value of these un-priced assets may be capitalized in house prices and rental rates.[12] Net farm income is approximately 0.51m Yen per farmed hectare per annum in Fukushima. A significant portion of this figure is composed of the various subsidies given to farming in Japan and therefore should properly be deducted from the net benefits of clean-up.[13] However if I take the figure at face value, it can be used as an estimate for b_0 for farmland. For residences, average prices for housing in Fukushima in 2009 were approximately 8.8m Yen for a 400m^2 residential site (Japan Statistical Yearbook 2010). If $r = 0.04$ this would suggest a b_0 of 352,000 Yen per annum per household. A weighted figure for benefits per hectare or per household is then calculated assuming that the benefits from workplace, forests and roads are capitalized in the values for farmland and households. Using this approach

[12] For woodlands etc. some flows of ecosystem services are unlikely to have been disrupted by the accidents. Recreation activities and forestry production will however be curtailed.
[13] OECD 2010, suggests that on average 47% of farm income comes from government support. The figure is typically higher for rice farming.

produces b_0=0.261m Yen per hectare or 0.483m Yen per household. If there were restrictions on farming after resettlement and farm income was zero then the benefit figures become, 0.19m Yen and 0.352m Yen respectively. An alternative to house values is provided by the rental figures for homes. Mean rental values for homes in Fukushima (Japan Statistical Yearbook 2010) were 39,160 yen per month in 2008, the last year for which figures are available. This rental-based figure yields b_0 values of 0.325m Yen per hectare per year or 0.600m Yen per household per year. Consequently for b_0, I use a range of 0.19m – 0.325m Yen per hectare per year with a central figure of 0.261m Yen.

For b_1, the starting point is the framework set out in the IAEA, 1994, where the effect of 1 man Sv is taken to be roughly equivalent to the loss of one life year. In this case, the value of a 1 m Sv/annum reduction in exposure for a household of n people is vn/1000 where v is the value of a statistical life year (VSLY). According to the Japan Statistical Yearbook, 2010, the average household size in Fukushima was 2.83 in 2009. For v, no official figure is available for Japan. The IAEA guidance sets v=GNP/capita, but this is low compared to many estimates used in the modern risk literature. For instance, Viscusi 2012, finds a range of values of VSLY US $ 150,000 to $400,000 for working age Americans (i.e. roughly 3 to 8 times GNP per capita). Abelson, 2007, offers a survey of international evidence and proposes a figure of approximately 3 x GNP per capita for official use in Australia. I therefore use a range of v = 1-5 per capita income with a central value of v=3, using Yen 2.7m as a guide for per capita income in Fukushima (Japan Statistical Yearbook, 2010). This gives a range for b_1 of 7,760 Yen to 38,800 Yen per mSv per annum per household, which at average population densities translates into 4,200 to 21,000 Yen per mSv per annum per hectare with a central figure of 12,600 Yen.

Table 1 here

3.2 Estimates of optimal delay.

I concentrate first on case 1. Figure 1 in the introduction provided a basic case showing the relationship between time of resettlement, costs and benefits. In this figure, I use the central case of r = 0.04, x = 50 and s = 5, b_0 =0.33m Yen, μ=0.559, b_1 =12600Yen and c=1.32m Yen (implying b_0/c = 0.261 and b_1/c=0.0095). Clearly both the net present value of costs and benefits both fall as resettlement is pushed into the future. But since costs fall more quickly than benefits, the optimal delay is positive and equal to 8.75 years. The net benefit curve is skewed right, so that the net benefits of immediate resettlement are no higher than the net benefits of delaying resettlement by 38 years.

I now consider how the central estimate changes with the underlying parameters. Figure 6 illustrates the relationship between optimal T and the ratio b_0/c ratio, for several combinations of initial exposure levels and targets for resettlement. For other variables I use the central values. At $b_0/c = 0.25$ the optimal delay ranges from 5.6 years (s=5, x = 20) to 16.6 years (s=1, x = 100). For b_0/c values that are more than double the central figure, optimal delay approaches zero and is not sensitive to changes in s and x within the range of figures used. However, if b_0/c is below 0.25 then optimal delay rises becomes more and more sensitive to changes in the ratio x/s. For some low b_0/c values, it is not optimal to actively decontaminate. For instance, for s=5, x = 20, active decontamination is not optimal when b_0/c falls below 0.13, which is above the ratio for farmland.

Figure 6. Optimal Delay and b_0/c .

For Figure 7 I vary μ – the fraction of excess dosage that remains after a clean-up. Other parameters are at their central values, except s, x and in two cases, $b_0/c=0.25$. For relatively low levels of contamination the optimal delay is not particularly sensitive to changes in the value of μ. If this fraction falls below 0.4, then optimal delay is less than 5 years. If, on the other hand μ is at 0.76, then T = 23.4 years. For higher values of contamination or lower benefit figures, optimal delay is much more sensitive to the efficiency of the clean-up process. For example, with x=100, an increase in μ from 0.55 to 0.6 doubles the optimal delay.

Figure 7. Optimal delay and the clean-up efficiency.

For Figure 8 the rate of interest is varied around the central value of 4% per annum. As in the previous case, higher x/s and lower b_0/c ratios raise the optimal delay and increase the sensitivity of delay to the interest rate. At interest rates of 6% per annum, for instance, T = 10.5 years for the central case and 54 years if x=100. For rates above 7%, the optimal strategy can be one of waiting for remediation to occur naturally. On the other hand, even at zero interest rates, delay of at least 4 years is optimal in all the cases depicted.

Figure 8. Optimal Delay and r

Varying the other important parameter, b_1/c around the central value has only a minor effect on delay times. For instance, doubling b_1/c from its central value increases optimal delay by less than one month. However, there is ample evidence (e.g. Savage, 1993) that many individuals dread particular risks – in other words they are willing to pay more to prevent or reduce some risks for a given change in the probability of death or ill-health. Jackson et al, 2006, consider the evidence for this in a radiation context, while NERA 2007 is a background report on the economic valuation of radiation risks prepared for the UK's Health and Safety Executive that also mentions the possibility. Takaaki Kato's (2006, 2010) relatively high contingent valuation figures for willingness to accept nuclear power risks in Japan is consistent with dread risks for exposure to elevated radiation doses. Meanwhile, the psychological after-effects of Chernobyl have been stressed in WHO, 2005 and Danzer and Weisshaar, 2009, while Lehmann and Wadsworth, 2011, provides quantitative evidence of the impact of Chernobyl-related psychiatric illnesses on subsequent labour market experience. In addition, some individuals may over-estimate risks, creating a question whether subjective or objective risks should be used in policy analysis (see Johansson-Stenman, 2008, or Munro, 2009). In this context, lost benefits from living in a contaminated area may not be fully restored when evacuation notices are removed and individuals are allowed to return home. The basic estimates of b_1 that I use omit this important but difficult to quantify element of stress and anxiety associated with raised exposure. Since, $\partial T/\partial b_1 \geq 0$ the omission yields a potential underestimate of optimal delay in case 1. For case 2 examined below, the omission potentially leads to an undervaluation of the case for intervention. Arguably also, benefits are fully restored only when the anxieties and fears associated with contamination are also removed. Specifically, there may be a premium for restoring exposure levels to their pre-accident levels. In addition, it may not be simply the dose level that creates psychological problems for some individuals, but also the departure from historical or reference levels of risk. Certainly, it is well-documented (e.g. Harley, 2008) that background doses vary significantly across the world, but I know of no evidence that anxiety-related psychological problems are generally correlated with background radiation risks. It is also reasonable that at least for some individuals, stresses arise from being away from the family home (Neria et al, 2008).

The IAEA model sets such issues aside, but they are potentially important from a policy perspective. In order to get some fix on how b_1 might be adjusted to include elements beyond those considered by the IAEA, I take some data from a recent survey of 1200 evacuated villagers (Itonaga and Uragami, 2012) conducted by a NGO which asks about intention or willingness to resettle at several different levels of residual exposure to radiation. This survey has a relatively low response rate that may make the results unrepresentative, but I use the information it provides as follows: suppose an individual receives a gain b_0/r from resettlement and a cost sb_1/r from subsequent exposure to dose s, then he or she will be willing to resettle provided $b_0 \geq sb_1$. In other words if b_0 is known along with the critical value of s at which she or he will resettle then I can estimate b_1. In this data set there is only a few discrete values of s (20, 5, 1 and 0) and but I can use them to construct a crude estimate of mean b_1 for the sample.[14] Given that 21.9% of the sample state that they would not wish to resettle even at 1mSv, the use of the village data gives a high value for $b_1 \approx 0.23b_0$. At this kind of level which is 4.8 times the central value, optimal delay depends very much on the target. When the target for resettlement is s=5, optimal delay is 10.8 years (compared to 8.75 in the central case). When the target is s=1, 20 years is optimal.

The figures in Table 2 build on the previous paragraph and show a different perspective on the sensitivity of the central estimates. In this table I consider several 'scenarios' separately and jointly. Changes (1) and (3) represent examples where policy can be adjusted to take into account variation in initial exposure levels. It is clear from these examples that a policy of leaving the most contaminated land to the last is optimal. Scenario (4) represents a change of policy in which the produce from once contaminated agricultural land is indefinitely banned from the market. In this case, the optimal delay is lengthened as the benefits from resettlement falls. Scenarios (2) and (5) illustrate the consequences in the feasibility and efficiency of the clean-up process. Raising the efficiency of clean-up to above 75% reduces the optimal delay significantly. On the other hand, if the decontamination process takes some time (4 years in the case of scenario (2)) optimal delay of resettlement is little affected, but obviously decontamination must begin 4 years before resettlement. The final individual scenario (6) represents a change in behaviour compared to the standard case. Here, it is supposed that individuals behave according to the plans stated in the Itonaga and Uragami, 2012 survey. In other words, if the target is 1mSv then 21.9% of the population do not return and so on. At the same time, the value of b_1 is consistent with the behaviour. Taken together this means that the benefits of incomplete decontamination are lower because fewer individuals and households return compared to the baseline scenario. But post-resettlement costs are generally higher, because the estimate of b_1 is higher compared to the central estimates.

[14] For the people who say they are willing to resettle at 20 mSv we do not know the upper threshold at which they would resettle. The choice of threshold makes almost no difference to the estimate of average b_1 but for these individuals I suppose it is exactly 20mSv. For the 13% of individuals who say they would follow expert advice I also suppose that they would also be willing to resettle at 20mSv.

Table 2 here.

A feature that emerges is that for most reasonable parameter values T=0 is not the best policy. Some delay almost always enhances the payoffs from decontamination. The scale of the gain from delay varies, but for instance, for the most negative scenario considered, (6), it is optimal to delay resettlement for 29.1 years. In the most positive scenario, (5), delay of only 3.8 years is desirable. The range is large because optimal delay is particularly sensitive to the efficiency of the clean-up and to the possibility that some individuals may not wish to resettle at a target value of s=5.

3.3 *Case 2: In-situ clean-up.*

I now turn to the case of in-situ clean-up. In case 2 for the central figures used above, no active decontamination is optimal. The reason is the combination of the initial rapid natural reduction in radiation coupled with the low value of b_1 produced using the IAEA model (and this is in keeping with the figures produced for IAEA 1994). The result is not sensitive to changes in the parameter values. For instance, raising the efficiency of the clean-up by changing μ to 0.36 does not alter the result. Similarly cutting the unit cost of cleaning by 40% or doubling the value of b_1 does not alter the conclusion. This can be understood better by considering the optimal level for the target. In case 2, the optimality condition is,

$$y\mu^n = \frac{c}{b_1 \ln(1/\mu)}\left(\frac{0.74}{r+0.3356\alpha}+\frac{0.26}{r+0.023\alpha}\right)^{-1} \qquad (4)$$

For the central values used above, this equation suggests an 'optimal' post-decontamination level of exposure of 23.6 mSv per year which is above the targets considered. This is perhaps not surprising given the underlying IAEA model. For higher values of b_1/c at the upper end of the range, (e.g. b_1/c =0.028), then the optimal target falls to 7.6mSv. With a 1% interest rate and highly effective cleaning such as μ=0.3 and b_1/c =0.028, then the target figure falls to 1.3mSv per year. If I take the much higher figure for b_1 based on Itonaga and Uragami, 2012, but otherwise revert to the central figures for other parameters then the optimal level is 4.6mSv. If I then set r=0.01, μ=0.3 the optimal level is 0.8mSv. In theory, if some active decontamination is optimal then some delay may also be optimal. However, with in-situ clean-up the value of the benefits of clean-up decay at approximately the same rate as the costs of cleaning. Thus, in practice interior optima for T are not typical. In short, when active decontamination is optimal in the in-situ case, it is generally not optimal to delay remediation efforts.

4 Conclusion.

The Japanese government has engaged in a high profile and costly attempt to decontaminate rapidly the affected land around Fukushima dai-ichi nuclear power plant. In this paper I have set out a framework for evaluating the economic value of active decontamination. The model set out is basic, but captures some of the major dimensions of the policy issue for a general case of land evacuated after a nuclear accident and for the specific case of Japan. What stands out is the lack of data for costs and benefits, both from Fukushima but also from previous incidents. Given this important caveat, it still seems that for most reasonable values of the parameters it is optimal to delay contamination for a period of 5-10 years. For some extreme values of resettlement benefits, delay of only 3 years is optimal, but at the same time if the reluctance of many former residents to move back is taken into account the optimal delay can be well above 15 years.

In the discussion of possible parameters, reasonable figures for the benefit to cost ratio differed between strategies that concentrated on urban assets and plans which also cleaned up farmland and adjacent woodlands. The ratio also varied depending on the extent of the contamination. The results therefore suggest that it may be optimal to have different policies for urban land and farmland, with greater delay for the latter. This is particularly the case if farmland produce cannot be sold for an extended period after resettlement. I am slightly cautious about such a conclusion for at least two reasons. First, the policy may not be feasible in areas where individuals are constantly moving between small villages and farmland. Secondly, it may not be optimal if the presence of nearby, untouched farm and woodland has significant negative external effects on resident's mental health. The model also points to the value of resettling relatively lightly contaminated lands first and delaying resettlement of areas with higher radiation levels (e.g. above 100mSv per annum).

The final point of the paper is the uncertain role of fear, anxiety and dread in resettlement and decontamination decisions. It is clear from Chernobyl that the psychiatric impact of elevated radioactive exposure can be significant and it is also clear that many former residents of the evacuated zone in Fukushima have significant fears about moving back, even after decontamination. However, a number of things are not so clear such as the relationship between policy choices and psychological stresses. For instance there may be significant discontinuities in the benefits if radiation is completely restored to its prior levels. Psychological factors may also be heterogeneous across the community and individual decisions about whether to resettle may be conditional on the behaviour of other former residents. All this requires more research.

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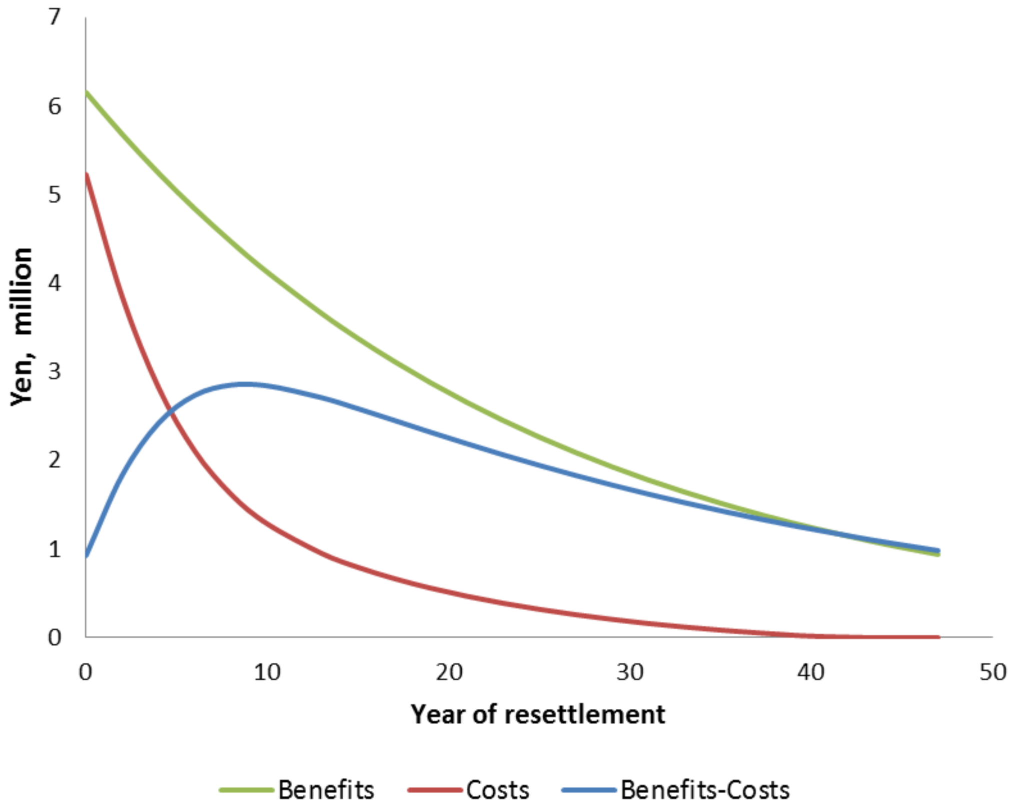
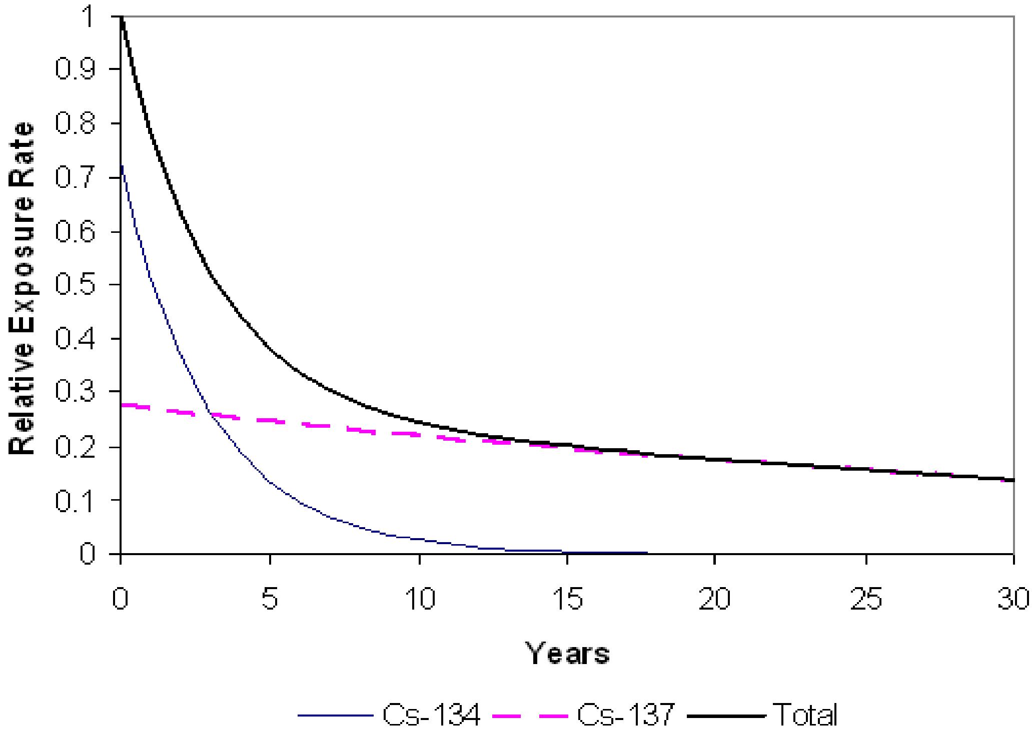

7
6
5
4
3
2
1
0
Yen, million
0
10
20
30
40
50
Year of resettlement
Benefits
Costs
Benefits-Costs

Figure 1



Relative Exposure Rate
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
Years
Cs-134
Cs-137
Total

Figure 2

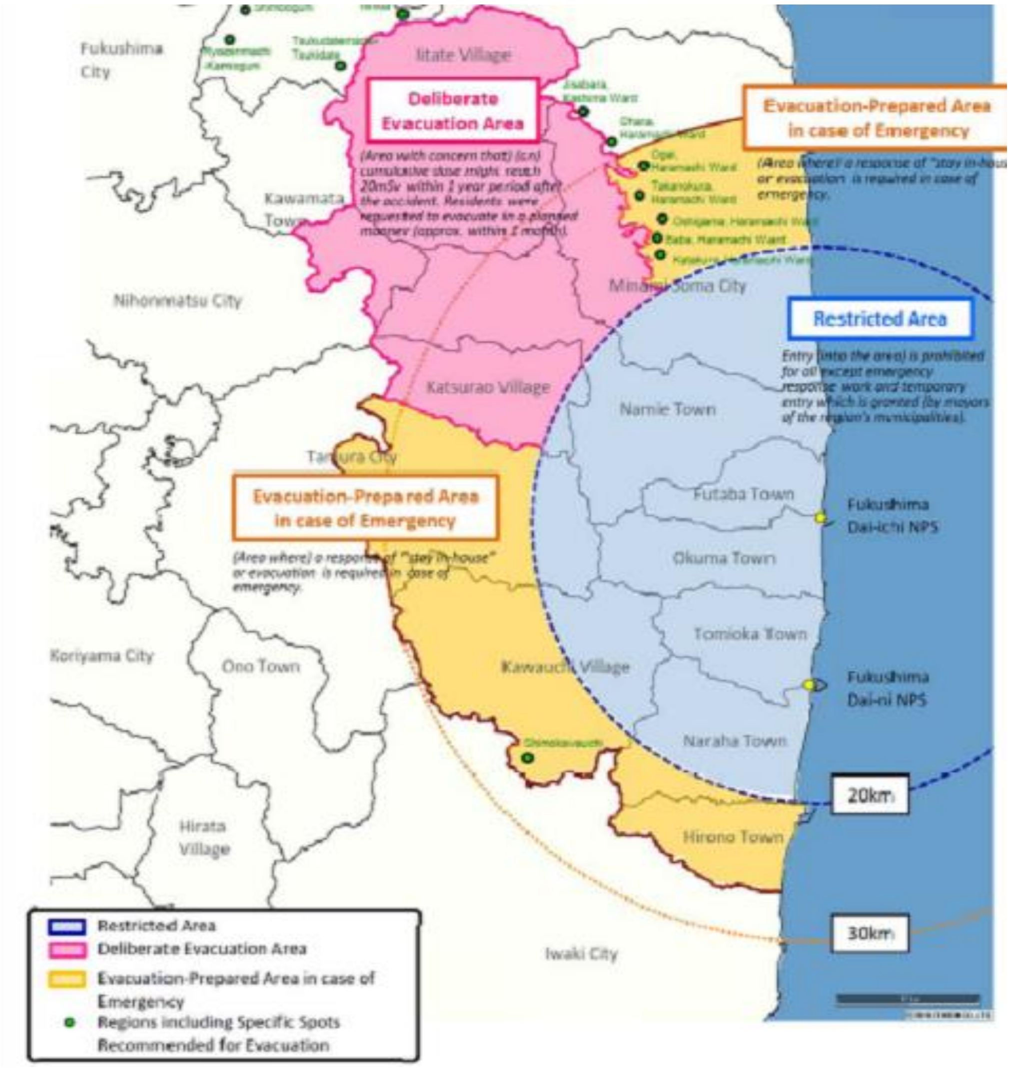

Fukushima City
Iitate Village
Deliberate Evacuation Area
Evacuation-Prepared Area in case of Emergency
Kawamata Town
Nihonmatsu City
Minami Soma City
Restricted Area
Katsurao Village
Namie Town
Tamura City
Evacuation-Prepared Area in case of Emergency
Futaba Town
Fukushima Dai-ichi NPS
Okuma Town
Tomioka Town
Koriyama City
Ono Town
Kawauchi Village
Fukushima Dai-ni NPS
Naraha Town
20km
Hirata Village
Hirono Town
30km
Iwaki City
Restricted Area
Deliberate Evacuation Area
Evacuation-Prepared Area in case of Emergency
Regions including Specific Spots Recommended for Evacuation

Figure 3

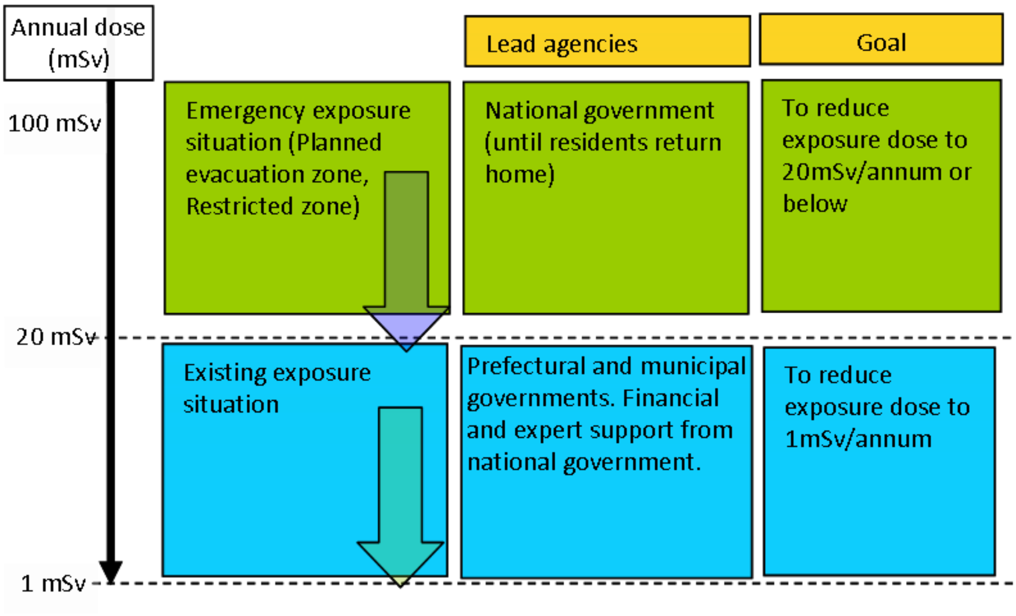
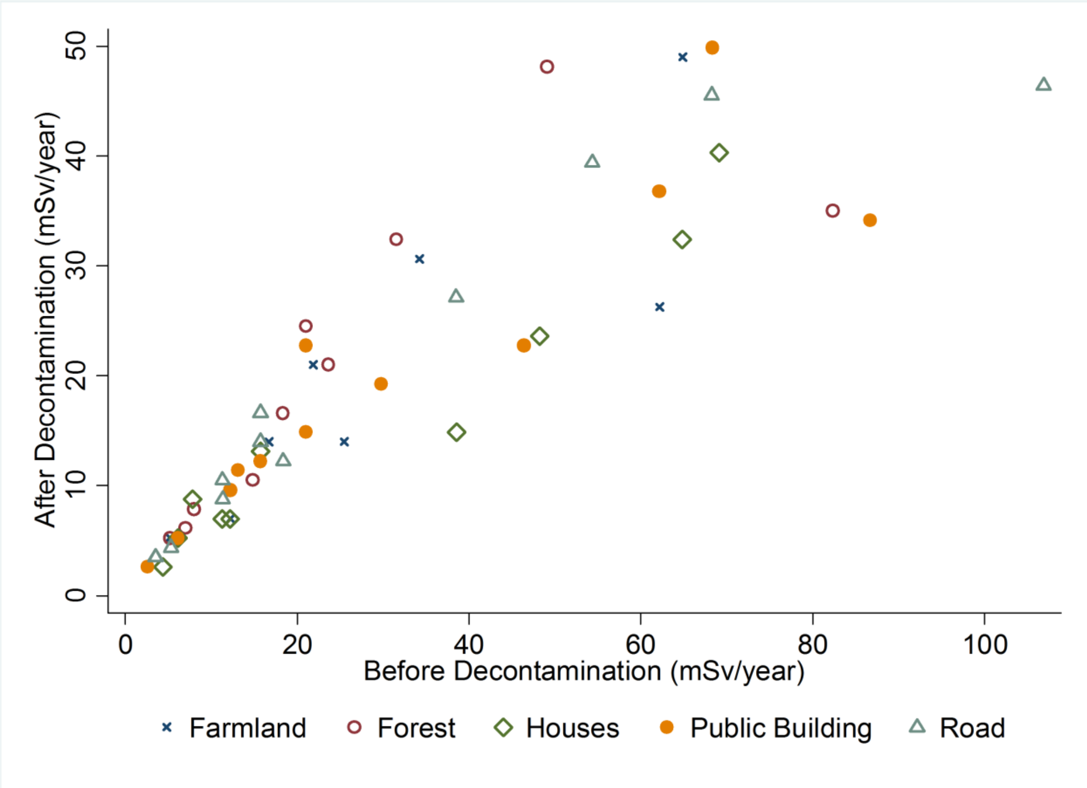

Annual dose (mSv)
100 mSv
20 mSv
1 mSv
Lead agencies
Goal
Emergency exposure situation (Planned evacuation zone, Restricted zone)
National government (until residents return home)
To reduce exposure dose to 20mSv/annum or below
Existing exposure situation
Prefectural and municipal governments. Financial and expert support from national government.
To reduce exposure dose to 1mSv/annum

Figure 4



After Decontamination (mSv/year)
0
10
20
30
40
50
0
20
40
60
80
100
Before Decontamination (mSv/year)
Farmland
Forest
Houses
Public Building
Road

Figure 5

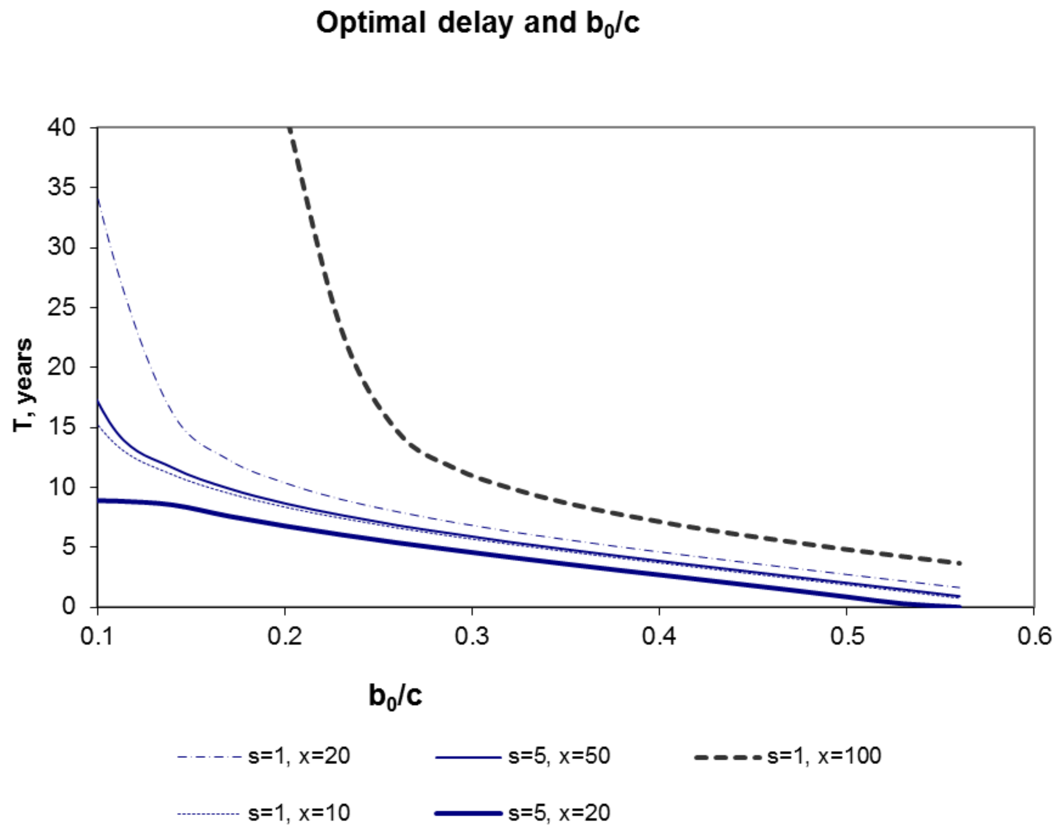

Optimal delay and b_0/c
T, years
40
35
30
25
20
15
10
5
0
0.1
0.2
0.3
0.4
0.5
0.6
b_0/c
s=1, x=20
s=5, x=50
s=1, x=100
s=1, x=10
s=5, x=20

Figure 6

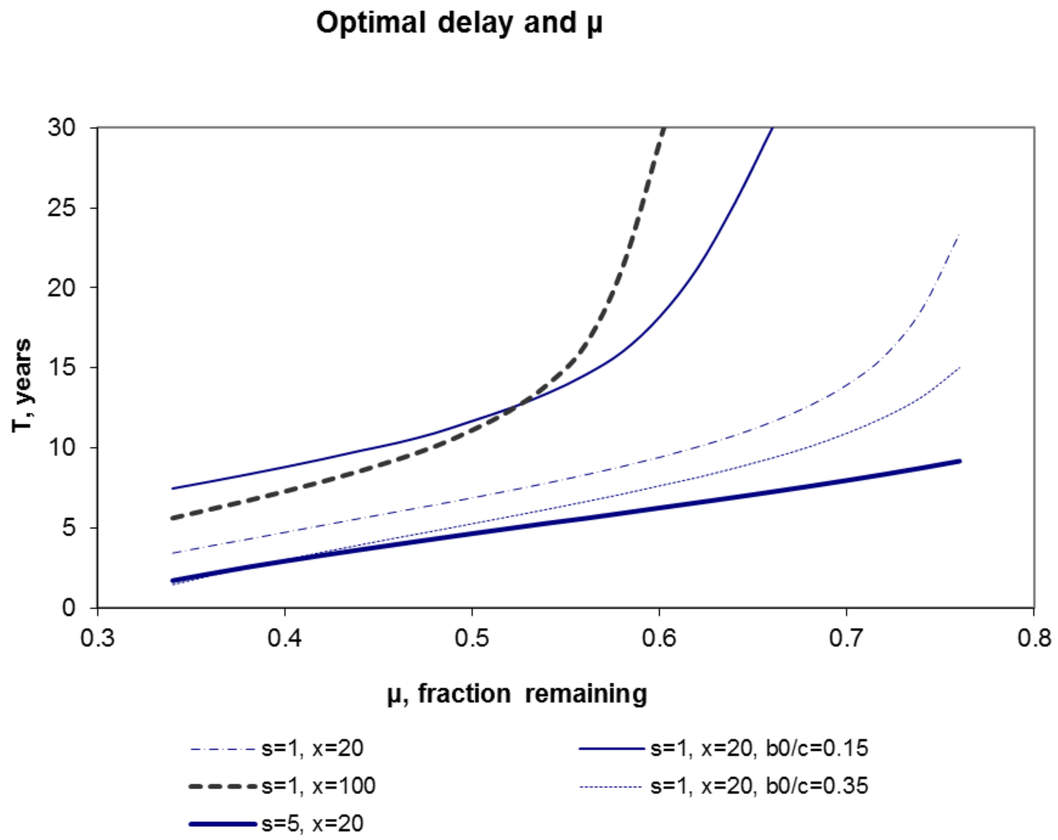
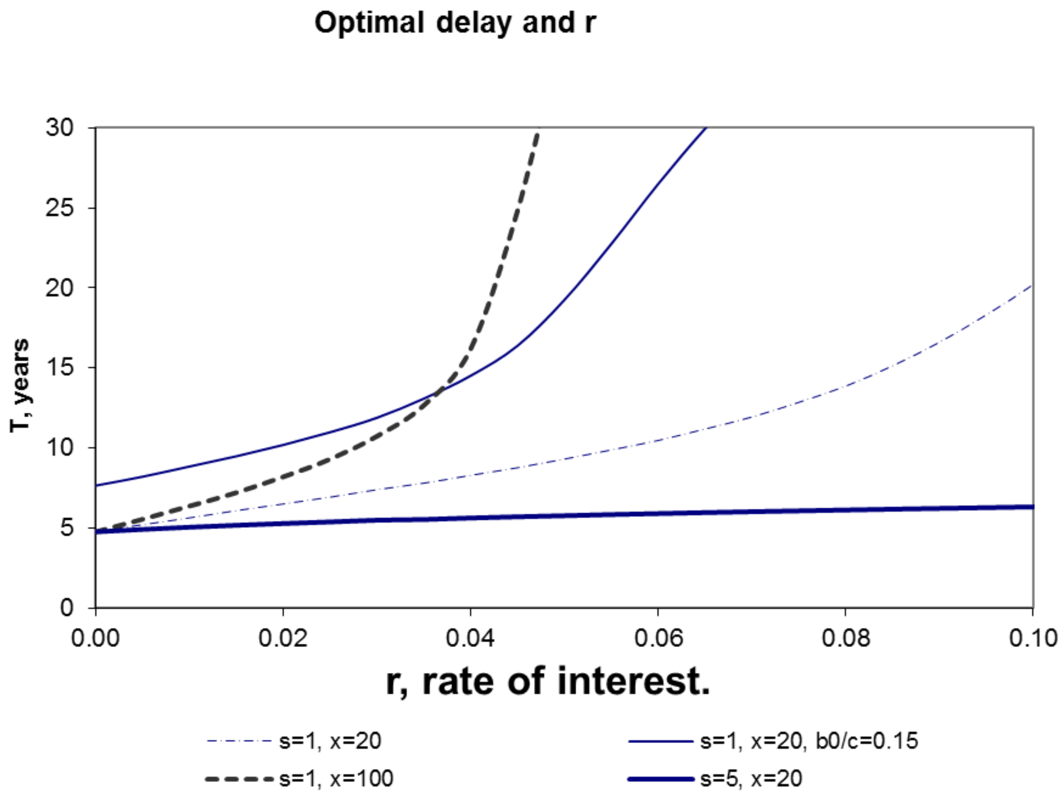

Optimal delay and μ
T, years
30
25
20
15
10
5
0
0.3
0.4
0.5
0.6
0.7
0.8
μ, fraction remaining
s=1, x=20
s=1, x=100
s=5, x=20
s=1, x=20, b0/c=0.15
s=1, x=20, b0/c=0.35

Figure 7



Optimal delay and r
30
25
20
15
10
5
0
T, years
0.00
0.02
0.04
0.06
0.08
0.10
r, rate of interest.
s=1, x=20
s=1, x=20, b0/c=0.15
s=1, x=100
s=5, x=20

Figure 8

Table 1. Parameters		
Parameter	Value or range	Basis for estimates
r, discount rate	1-10% per annum	Japanese long-term interest rates
α, decay rate shift parameter	1	Caesium decay rates, IAEA, 2011.
s, target	1-20 mSv per annum per person	Japanese government policy, Moriya 2011
x, starting point	10-100 mSv per annum per person	Current exposure (2012) in restricted and evacuated zones
c, cost	0.75m Yen – 1.32m Yen per clean-up exercise per standard hectare	Estimated clean-up costs (Fukushima, 2011)
μ, fraction dose remaining after a clean-up exercise	0.36-0.76	Pilot demonstration projects JAEA 2012
b_0 benefit of resettlement	0.19-0.32m Yen per annum per standard hectare	House and land income or values; profit from farming
b_1 benefit from reduced exposure	0.0042-0.021m Yen per mSv per annum per standard hectare	IAEA equation and estimated clean up costs (Fukushima, 2011).
n, person per household	2.83 people	Japan Statistical Yearbook, 2010 for Fukushima
v, value of a statistical life year	1-5 GNP per capita	GNP: Japan Statistical Yearbook, 2010 for Fukushima,

Table 2. Scenarios.

Case	Standard	Higher contaminated area (1)	Time to clean (2)	Lower contaminated area (3)	Agricultural interdiction (4)	More efficient cleaning (5)	Reluctant return (6)	Positive changes (3)+(5)	Negative changes (2)+(4)+(6)
Underlying change to assumptions	-	Resettlement of more heavily contaminated area	4 year cleaning period	Resettlement of less contaminated area	No farm income after return	Rate of clean-up improves	Only 39% population return at 5mSv; 78% at 1mSv	Positive changes combined	Delaying changes combined
Change to parameters from standard	(b_0= 0.26; c=1.32, x=50, s=5, μ=0.56, r=0.04)	x=100	4 year cleaning period, c=1.43	x=20	b_0= 0.19	μ=0.36	b_0= 0.146 until 1mSv then b_0=0.22 (b_1 consistent)	x=20, μ=0.36	b_0= 0.146 then b_0 = 0.22; c = 1.43, x=100
Period before resettlement (years)	8.75	10.84	9.34	6.77	11.37	5.00	16.5	3.8	29.1

Appendix (supplementary): Comparative statics for T.

For the delayed clean-up sub-case, starting with,

$T = \frac{1}{r} + \frac{\ln(x/s)}{a} + \ln(1/\mu)\left(\frac{-b_0}{acr} + \frac{sb_1}{ac(a+r)}\right)$, the comparative statics for T are as follows:

$$\frac{\partial T}{\partial c} = \frac{\ln(1/\mu)}{ac^2}\left(\frac{b_0}{r} - \frac{sb_1}{a+r}\right) > 0$$

$$\frac{\partial T}{\partial x} = \frac{1}{ax} > 0$$

$$\frac{\partial T}{\partial s} = -\frac{1}{sa} + \ln(1/\mu)\left(\frac{b_1}{ac(a+r)}\right)$$

$$\frac{\partial T}{\partial b_0} = -\frac{\ln(1/\mu)}{acr} < 0$$

$$\frac{\partial T}{\partial b_1} = \frac{s\ln(1/\mu)}{ac(a+r)} > 0$$

$$\frac{\partial T}{\partial r} = -\frac{1}{r^2} + \frac{\ln(1/\mu)}{ac}\left(\frac{b_0}{r^2} - \frac{sb_1}{(a+r)^2}\right) > 0$$

$$\frac{\partial T}{\partial \mu} = \frac{(1/\mu)}{ac}\left(\frac{b_0}{r} - \frac{sb_1}{(a+r)}\right) > 0$$

$$\frac{\partial T}{\partial a} = -\frac{\ln(x/s)}{a^2} + \ln(1/\mu)\left(\frac{b_0}{a^2cr} - \frac{(2a+r)sb_1}{a^2c(a+r)^2}\right)$$

The ability to sign ∂T/∂r comes from the fact that in sub-case (ii) $1 + \ln(1/\mu)\left(\frac{-b_0}{ac} + \frac{rsb_1}{ac(a+r)}\right) < 0$. This in turn implies that $\left(\frac{-b_0}{ac} + \frac{rsb_1}{ac(a+r)}\right) < 0$ which means we can also sign ∂T/∂c and ∂T/∂μ .