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The cost of nuclear power generation critically depends on the damages caused by plant failure. We estimate the residential land damage caused by the failure of the Fukushima Daiichi nuclear power plant, as it forms a substantial part of the total damage, by observing the change in transaction prices before and after the accident with the degree of radioactive contamination. The estimates based on hedonic price equations, with the degree of radioactive contamination measured by airborne surveys, indicate that the contamination significantly decreased the price of residential land. The estimated total residential depreciation ranges from 2.19 to 2.65 trillion yen, approximately equivalent to 21.9–26.5 billion US dollars, or about 0.5% of Japan's GDP.

JEL: Q51; Q53; R31

Keywords: Fukushima; Nuclear Power Plant; Land Property Damage; Radioactive Contamination; Land Contamination.

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I. Introduction

How high is the cost of nuclear power generation? The radioactive contamination caused by the collapse of the Fukushima Daiichi nuclear power plant showed the cost of nuclear accidents and sparked international debates on a country's reliance on nuclear power generation. Immediately after the accident, Germany adopted a long-term plan to cease the operation of nuclear power plants, whereas the United Kingdom reconfirmed the continuation of its energy policy of reliance on nuclear power generation (Jahn and Korolczuk (2012) and Wittneben (2012)). While the opponents to the continuation of nuclear power plant operation, including Naoto Kan, the Prime Minister of Japan at the time of the accident, argue that the potential costs of a nuclear power plant failure is prohibitively high (Tabuchi (2011)), the proponents argue that the hike in energy prices and the increase in CO2 emissions from the abandonment of nuclear power generation outweigh the potential costs of plant failure, which is now within a reasonable range following the progress in safety engineering (Hong, Bradshaw and Brook (2013), Hayashi and Hughes (2013), and Zhang et al. (2012)).

After all, the economic discussion surrounding nuclear power generation boils down to the cost–benefit analysis of its operation. We cannot, however, calculate the cost of nuclear power generation without information on property damage caused by a nuclear incident. The committee for the examination of the costs of various methods of power generation, established in the cabinet office of the Japanese government, reports the lower bound of the cost estimate, but does not report the upper bound, because the committee members can agree only on the lower bound of the damage caused by potential accidents (Examination Comittee on Power Generation Costs (2011)). Residential land property damages caused by radioactive contamination arguably comprise a significant portion of the total property damage caused by nuclear power plant failures. We therefore estimate the residential land property damage caused by radioactive contamination from the Fukushima accident. We, of course, cannot generalize the costs estimated from a single accident as the cost of all nuclear power plant accidents, but the Fukushima incident undoubtedly offers an important benchmark.

We estimate the hedonic land price equation by using real estate transaction data of 10 prefectures contaminated by radioactive fallout from the Fukushima Daiichi power plant, covering one year before and after the accident. We merge the real estate transaction data with the degree of radioactive contamination recorded eight months after the accident using a detailed geographic unit (*cho* or*oaza*) as the key. We include the geographic unit fixed effects to allow for the correlation between the unobserved land characteristics and proximity to the nuclear power plant.[1] Conditional on the location fixed effects, we argue that the degree of radioactive contamination in each area is randomly determined by meteorological conditions. We also take into account the potential sample selection bias caused by reduction in real estate transactions in the contaminated area. Furthermore, to minimize the effects of other damages caused by the East Japan Earthquake, we allow for differential price changes across prefectures or between coastal and non-coastal municipalities and confirm the robustness of the results. The most preferred estimation result indicates that a 10% increase in radioactive contamination decreases the residential land price by 0.23%. From this result and the total area of radioactive contamination, we estimate the total land property damage as about 2.65 trillion yen, almost equivalent to 26.5 billion US dollars, or about 0.5% of Japan's GDP.

Previous studies estimate the property damage of soil contamination by estimating the hedonic price equation (see Boyle and Kiel (2001) for a review and Currie et al. (2013) for a recent contribution), but few studies examine the effect of radioactive contamination because of the rarity of such cases. Gamble and Downing (1982) and Nelson (1981) estimated the impact of the Three Mile Island nuclear power plant failure on the land price of the surrounding area. These

[1]Recent studies on the effect of environmental quality on property prices or rent have paid particular attention to the endogeneity caused by the correlation between the observed environmental amenities and unobserved location characteristics. Examples include Chay and Greenstone (2005), Boes and Nesch (2011), and Davis (2011).

studies use the distance from the accident site as a proxy for land damage, and do not consider the measured radioactive contamination. Both studies do not find any fall in land prices of the surrounding areas after the accident. To the best of our knowledge, no study has systematically examined the land damage caused by the Chernobyl accident.[2] Outside Japan, several studies have examined the change in prices of land in areas around nuclear power generators after the Fukushima accident. Fink and Stratmann (2013) examined whether the accident decreased land prices in areas near nuclear power plants in the United States through risk recognition, but found no significant results. Bauer, Braun and Kvasnicka (2013) examined the change in transaction prices around nuclear power plants in Germany after the Fukushima accident, and found a decline in prices in the surrounding area, mainly because (planned) shut downs of nuclear power plants decreased the local economic activity and demand for land.

To date, Yamane, Ohgaki and Asano (2013) is the only study to have systematically examined the land property damage caused by the Fukushima accident using a hedonic approach based on measured radioactive contamination. They found that radioactive contamination significantly decreased the land price evaluation of licensed real estate appraisers as of July 2011 used for property taxation. We do not consider their results to be definitive because the manner in which professional appraisers evaluate the effect of an unprecedented event like radioactive contamination after four months of the event is not well understood. We contribute to the literature by estimating the total damage using transaction prices. Our estimate complements the mechanical damage estimate of the investigation committee on the finance and management of the Tokyo Electric Power Company. The committee estimated the total property damage of the evacuated area to be 570.7 billion yen, based on the property values used by local municipalities to determine property taxes. The committee assumed that property value depreciates

[2]Numerous studies have examined the impact of the Chernobyl accident on health outcomes. The works by economists include Almond, Edlund and Palme (2009) and Halla and Zweimller (2014).

to zero in the evacuated area, but neglected the radioactive fallout outside the official evacuated area. Our estimates overcome these limitations by considering the change in transaction prices over a wider area.

II. Data

We use two sets of data to construct the analysis sample for the estimation of the hedonic property price equation. The first set deals with the real estate transactions before and after the Fukushima accident by geographic location. The second set measures the degree of radioactive contamination after the accident by geographic location.

The data source for the first set is the Land General Information System maintained by the Ministry of Land, Infrastructure, Transportation and Tourism. The ministry sends a survey to all the new owners of real estate registered with the regional legal affairs bureau. The survey covers all real estate transactions of land without buildings, land with detached houses, and existing condominiums. The timing of transactions is recorded on a quarterly basis. We obtained the micro data of each transaction from the ministry's web page. We restrict the analysis sample to observations from 10 prefectures near the Fukushima prefecture (Iwate, Miyagi, Fukushima, Ibaraki, Tochigi, Gunma, Saitama, Chiba, Tokyo, and Kanagawa) between the second quarter of 2010 and the first quarter of 2012, covering from one year before to one year after the Fukushima Daiichi failure.[3]

We set a relatively short analysis time frame to pick up the short-term price responses to radioactive contamination. We also restrict the analysis sample to transactions involving land without buildings, because properties with housing units are likely to be currently occupied and transactions of such properties are likely to involve a time lag. It is worth noting that transactions without housing units are common in Japan, accounting for one-third of the total transactions in the sample period. Note that this sample restriction does not limit our estimates

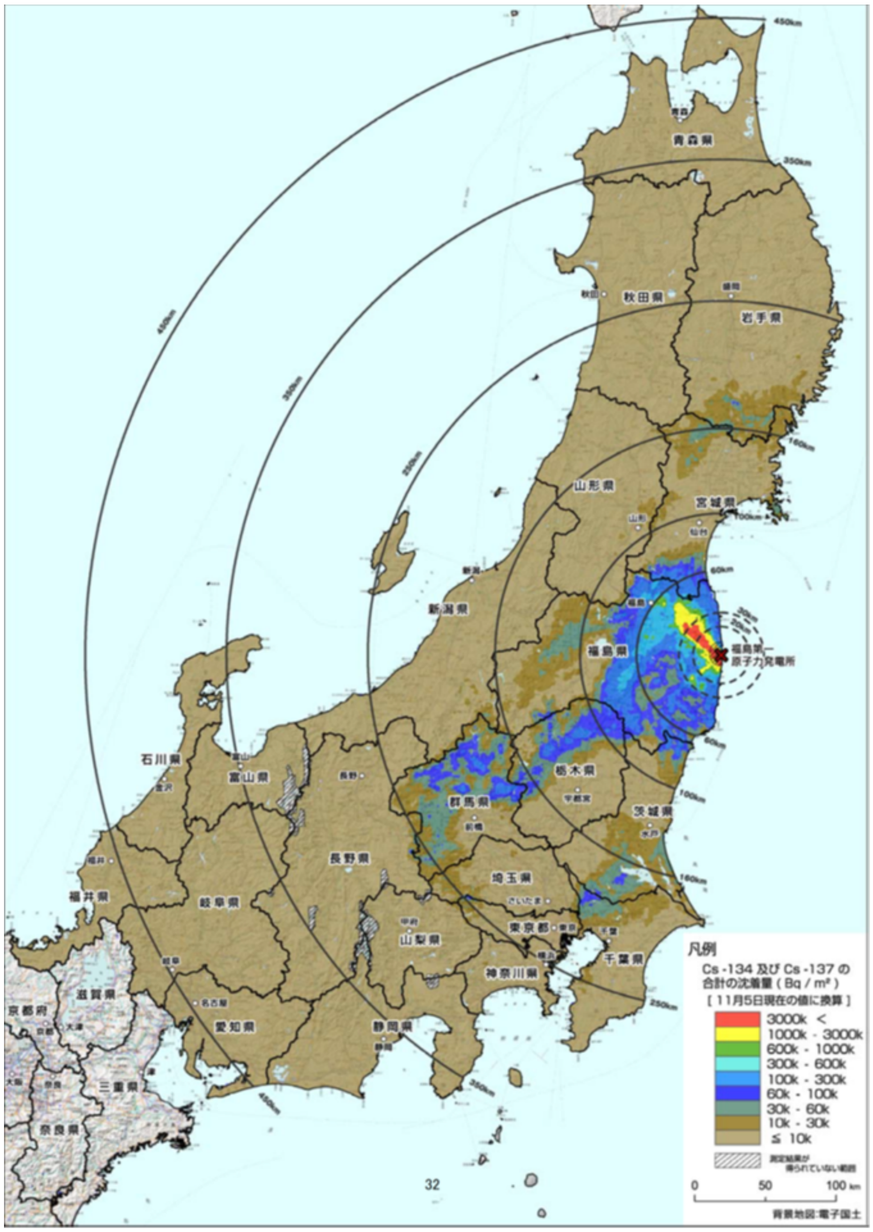
[3]The East Japan Earthquake and failure of the Fukushima power plant occurred in March 2011. The first quarter of 2011 is classified as pre-accident period throughout this paper.

of total residential land damage because we eventually multiply the estimated land price reduction by the total land area contaminated by radioactive fallout, including the area with housing units. As for transactions involving land, the survey records the attributes of each transacted real estate, including the location, price, area, and shape of the land; the width of the facing road; regulations on land use; the name of the nearest train station or bus stop; and the distance to the nearest train station or bus stop. We use the price per square meter of land as the dependent variable of the analysis and the attributes of land as the covariates.

The second data source is the results of the airborne survey conducted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Figure 1 is the monitoring result that maps the degree of soil contamination by cesium-134 and cesium-137 per square meter, as of November 5, 2011 (see Yoshida and Kanda (2012) for brief explanation). The map classifies the degree of contamination in nine categories: (1) 10 kilobecquerel (kBq) or less, (2) 10–30 kBq, (3) 30–60 kBq, (4) 60–100 kBq, (5) 100–300 kBq, (6) 300–600 kBq, (7) 600–1000 kBq, (8) 1000–3000 kBq, and (9) more than 3000 kBq. We import this map into a geographic information system software (GIS) and identify the highest degree of contamination within a detailed geographic unit (*cho* and *oaza*). The distribution of radioactivity is determined by not only the distance from the plant, but also the meteorological conditions after the explosion of the reactor covers. A series of explosions affect different regions depending on the movement of plumes and rainfall. Two meteorological events were particularly important in determining soil contamination: the rainfall on March 15 in the northwest and west of the plant that intensely contaminated the areas, and the rainfall on March 21 that contaminated the area 200 km south of the plant (Yoshida and Takahashi (2012) and Mathieu et al. (2012)).

We match the transaction data with the radioactive fallout data using geographic units (*cho* and *oaza*) as the key variables. The analysis data include 59,625 land transactions from 10,009 geographic units. Table 1 reports the descriptive

Figure 1. : The density of cesium-134 and cesium-137, as of November 5, 2011



Source: The results of the airborne survey conducted by the Ministry of Education, Culture, Sports, Science and Technology.

Table 1—: Descriptive Statistics of Analysis Sample

	Residential land: N = 59618			
	Mean	S.D.	Min	Max
Dependent variable				
Transaction price:	14.403	20.581	0.000	690.141
10 thousand yen per square meter				
Independent variable				
Cesium 134/137 $mBq/m^2\times$ After	0.007	0.030	0	2
Priority contamination survey area	0.074	0.261	0	1
$\times$ After				
Types of land shape				
Almost rectangular or square	0.065	0.247	0	1
Almost square	0.059	0.235	0	1
Square	0.010	0.100	0	1
Almost trapezoid	0.096	0.294	0	1
Trapezoid	0.039	0.193	0	1
Almost rectangular	0.317	0.465	0	1
Rectangular	0.236	0.425	0	1
Not facing road	0.022	0.148	0	1
Bad shape	0.156	0.363	0	1
Land use regulation				
Residential area	0.657	0.475	0	1
Commercial area	0.068	0.251	0	1
Manufacturing area	0.069	0.253	0	1
Other purposes area	0.206	0.405	0	1
Building-area ratio $\times$ city planning area	57.911	9.365	30	80
Floor-area ratio $\times$ city planning area	178.304	78.443	50	800
Transaction timing				
2Q-2010	0.139	0.346	0	1
3Q-2010	0.147	0.354	0	1
4Q-2010	0.148	0.355	0	1
1Q-2011	0.116	0.320	0	1
2Q-2011	0.127	0.333	0	1
3Q-2011	0.130	0.337	0	1
4Q-2011	0.126	0.332	0	1
1Q-2012	0.067	0.250	0	1

Table 2—: Change in number of transactions by degree of contamination

	Before (Q2-2010 Q1-2011)	After (Q2-2011 Q1-2012)	% Change
0-10 kBq	25,616	21,273	-17.00%
10-30 kBq	3,413	2,831	-17.10%
30-60 kBq	1,951	1,515	-22.30%
60-100 kBq	894	632	-29.30%
100-300 kBq	673	461	-31.50%
300-600 kBq	221	122	-44.80%
600-1000 kBq	1	1	0.00%
1000-3000 kBq	13	1	-92.30%
All	32,782	26,836	-18.10%

statistics of the analysis sample. Note the sharp drop in transactions in the first quarter of 2012 in the sample period.

Radioactive contamination may have reduced the land value to a level where transactions could not occur. How did the outbreak of the Fukushima accident and the subsequent radioactive contamination affect the number of land transactions? Table 2 tabulates the number of transactions by the degree of radioactive contamination, dividing the sample period into before and after the accident. It is worth noting that the majority of transactions took place in the less-contaminated areas in the pre-accident period, reflecting the fact that many of the transactions took place around the Tokyo metropolitan area that is relatively far from the Fukushima site. The total number of transactions decreased by 18.10% after the accident in the sample, but the reduction in percentage varies across areas, depending on the degree of contamination. The reduction in transactions is 17.00% in areas where the contamination is 10 kBq or less, and 44.80% in areas where the contamination is 300–600 kBq.

The more contaminated the land is after the accident, the fewer the transactions that take place on it. This empirical pattern does not contradict the hypothesis that radioactive contamination decreases the value of land down to a point where no transactions occur. This decrease in transactions, most probably due to the

Table 3—: Change in average land transaction prices, in thousand yen per square meter, by the degree of contamination

	Before (Q2-2010 Q1-2011)	After (Q2-2011 Q1-2012)	% Change
0-10 kBq	16.66	16.42	-1.40%
10-30 kBq	8.40	8.28	-1.50%
30-60 kBq	5.82	5.69	-2.10%
60-100 kBq	4.38	3.83	-12.60%
100-300 kBq	2.86	2.56	-10.50%
300-600 kBq	3.24	2.92	-9.70%
600-1000 kBq	1.24	0.21	-83.10%
1000-3000 kBq	1.14	0.09	-91.90%
All	14.44	14.36	-0.50%

radioactive contamination following the Great East Japan Earthquake and its aftershocks, may result in underestimation of the land damage because the areas severely damaged are not transacted on after the accident and do not appear in our sample.

We next examine the change in prices of transacted land. Table 3 tabulates the land price per square meter by the degree of radioactive contamination. The aggregate average land price virtually shows no change between the pre- and post-accident periods. The less-contaminated areas generally show higher transaction prices, reflecting the fact that land prices in the Tokyo metropolitan area are high and that the area is relatively far from the Fukushima accident site. An increase in radioactive contamination is generally associated with a decrease in land price. Land prices fell by a mere 1.4% in the area virtually not contaminated (less than 10 kBq), whereas they fell by around 10% in areas contaminated by 60–600 kBq (deep to light blue area in Figure 1).

Descriptive statistics show that the degree of radioactive contamination is negatively associated with both the number of transactions and land prices. These findings suggest that radioactive contamination of land depreciates the value of residential land. The rough tabulation, however, prevents us from identifying the causal impact of radioactive contamination on the value of residential land, as we do not control for the change in land attributes between the pre- and post-accident periods and because of the sample selection bias caused by missing transactions. The hedonic approach in the next section addresses the first issue, while the sample selection correction in the discussion section addresses the second issue.

III. Hedonic approach

A. Basic model

We model the natural logarithm of land price per square meter as determined by the following hedonic price equation:

$$\ln p_{ijt} = \beta_0 + \beta_1 w_t \cdot \ln z_j + x_{it}\gamma + c_j + d_t + f_{jt} + u_{ijt}, \tag{1}$$

where i is the index for a transaction; j is the index for the regional unit (*cho* or *oaza*); t is the index for the quarter; p_{ijt} is the transacted price of land per square meter; w_t is the dummy variable representing post-accident transactions; z_j is the midpoint of each measured radioactive density range in the post-accident period; x_{ijt} is the vector of dummy variables for land attributes, including the shape of land, the regulation on land use, and the dummy variables for quarters; c_j is the time-invariant unobserved characteristics of region j (10,009 geographic units); d_t is the year-quarter fixed effect; f_{jt} is the time-variant unobserved characteristics of region j at time t; and u_{ijt} is the idiosyncratic disturbance.

The model assumes a log–log relationship between the degree of contamination and price of land. Using the price logarithm as a dependent variable is desirable because a change in the explanatory variable has a proportional effect on the pre-accident price and it is indeed widely used in the literature (Boyle and Kiel (2001)). For the independent variable, the sample size, particularly of the contaminated areas, is not large enough to estimate separate coefficients for the dummy variables corresponding to each contamination level. To overcome the problem of imprecise estimations, we transformed the classified variables corresponding to contamination levels to continuous variables, using the midpoints for each range. We apply the Box-Cox transformation to the continuous variable such that $(Z^{\lambda} - 1)/\lambda$, in which $\lambda = 0$ corresponds to a log transformation and $\lambda = 1$ corresponds to a linear transformation. We estimate the above model with other covariates by changing λ from 0 to 1, with 0.01 increments and maintaining R^2. The best fit of the model is attained at $\lambda = 0.34$, with $R^2 = 0.3430$. The fit is much better than the model with $\lambda = 1$ that attains $R^2 = 0.3410$, but almost identical to the model with $\lambda = 0$ that attains $R^2 = 0.3429$. Given these Box–Cox trial results, we adopted the log–log specification. Note that most other covariates, except for the floor-area and building-area ratios, are dummy variables and there are no functional form issues.

The time-invariant region-specific price component apparently has a negative correlation with the degree of contamination with regard to proximity to the Fukushima Daiichi nuclear plant. The densely contaminated area, which is close to the power plant, was cheap even in the pre-accident period, as Table 3 indicates. This is partly because of the location of the nuisance facility in the area, but mostly because of the endogenous locational choice of the nuclear power plant. Ando (2015) documents that poor rural local municipalities accepted the nuclear power plant in the hope of local job creation and an increase in tax revenue. This endogenous location of the nuclear power plant creates the correlation between $\ln z_j$ and c_j. To allow for the correlation between $\ln z_j$ and c_j, we estimate the model by a fixed effects estimation, treating c_j as the fixed effect.

The key identifying assumption of our estimation is the non-correlation of $\ln zj$ and f_{jt}, conditional on other covariates and regional fixed effects. The geographic spread of radioactive fallout after a power plant failure is almost entirely dependent on the timing of the explosion of the structures that cover the nuclear reactors and the meteorological conditions around the time of the explosion, as suggested by several simulation studies (Yoshida and Takahashi (2012) and Mathieu et al.

(2012)). Therefore, we believe that the post-accident degrees of contamination and the time-variant regional shocks are not systematically correlated. We, however, account for the presence of f_{jt} and its possible serial correlation by making the standard errors robust against regional level clustering (Bertrand, Duflo and Mullainathan (2004)).

B. Parameter estimates for the hedonic equation

Column (1) of Table 4 tabulates the regression results of residential land price on the logarithm of degree of radioactive contamination and the other characteristics of land. The coefficient for the interaction term of the logarithm of radioactive fallout and the post-accident dummy variable are estimated to be negative and statistically significant. The estimated coefficient, -0.023, implies that a 1% increase in contamination decreases the residential land price by 0.023%. To make sense of the magnitude of this estimate, we compare the price change of areas designated by brown ($\leq 10k$) and deep blue ($60k - 100k$, a part of Kashiwa city in Chiba prefecture for example) in Figure 1. The log difference of the contamination is $\ln(80) - \ln(5) = 1.610$, because the midpoint of each range is used in the regression. Therefore, the deep blue region suffered from a 3.7% ($0.023 \times 1.610 \approx 0.037$) decrease in land price compared with the brown region. A similar calculation shows that the light blue region ($300k - 600k$, a part of Fukushima city, for example) suffered from a 10.3% price decrease.

The coefficients for the other independent variables are quite standard. A good shape of the land increases the price. Being designated as a commercial area increases the price, while being designated as a manufacturing area decreases the price. Facing more lenient regulations on building-land or floor-land ratio increases the price of land.

Table 4—: Determination of residential land price
Sample period: 2Q 2010–1Q 2011
Dependent Variable: ln(10 thousand yen per square meter)

	(1) OLS	(2) OLS	(3) IV	(4) OLS	(5) OLS
ln(Cesium 134/137 mBq/m^2)	-0.023	-0.020	-0.029	-0.019	-0.029
$\times$ After	(0.007)	(0.008)	(0.008)	(0.011)	(0.007)
Types of land shape (Base category: Almost square or rectangular)					
Almost square	0.155	0.155	0.155	0.155	0.151
	(0.018)	(0.018)	(0.015)	(0.018)	(0.018)
Square	0.171	0.171	0.171	0.170	0.166
	(0.030)	(0.030)	(0.028)	(0.030)	(0.030)
Almost trapezoid	0.032	0.032	0.032	0.032	0.031
	(0.017)	(0.017)	(0.014)	(0.017)	(0.017)
Trapezoid	0.066	0.066	0.066	0.066	0.068
	(0.021)	(0.021)	(0.017)	(0.021)	(0.021)
Almost rectangular	0.088	0.088	0.088	0.088	0.087
	(0.015)	(0.015)	(0.012)	(0.015)	(0.015)
Rectangular	0.112	0.112	0.112	0.113	0.111
	(0.016)	(0.016)	(0.012)	(0.016)	(0.016)
Not facing road	-0.126	-0.126	-0.126	-0.127	-0.127
	(0.021)	(0.021)	(0.020)	(0.021)	(0.022)
Bad shape	-0.186	-0.186	-0.186	-0.186	-0.185
	(0.017)	(0.017)	(0.013)	(0.017)	(0.017)
Land use regulation (Base category: Residential area)					
Commercial area	0.124	0.124	0.124	0.122	0.122
	(0.025)	(0.025)	(0.018)	(0.024)	(0.025)
Manufacturing area	-0.014	-0.014	-0.014	-0.014	-0.011
	(0.018)	(0.018)	(0.014)	(0.018)	(0.018)
Other purposes area	-0.696	-0.696	-0.696	-0.696	-0.697
	(0.034)	(0.034)	(0.014)	(0.034)	(0.034)
Regulation in town planning area					
Building-area ratio	0.002	0.002	0.002	0.002	0.002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Floor-area ratio	0.001	0.001	0.001	0.001	0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Inverse Mill's ratio	-	0.020	-	-	-
		(0.025)			
Time F.E.	Y	Y	Y	Y	Y
District F.E.	Y	Y	Y	Y	Y
Time $\times$ prefecture F.E.	N	N	N	Y	N
Time $\times$ coastal district F.E.	N	N	N	N	Y
F-statistics for the first stage	-	-	55,433	-	-
Observations			59,618		

Note: Standard errors that are robust against the regional unit level clustering are reported in parentheses. Block bootstrapped standard errors with 500 repetitions are reported for Column (2). The dummy variable for the priority contamination survey area is used as the instrumental variable for Cesium 134/137 mBq/m^2 for Column (3).

IV. Discussion

A. Correcting for the sample selection bias

The residential land damage estimated using the hedonic price equation may underestimate the true damage because the equation is estimated conditional on transactions taking place. As seen in Table 2, radioactive contamination seems to reduce land transactions. A sample selection bias occurs when seriously damaged properties within a radioactive contamination cell disappear from the land transaction record. This sample selection attenuates the negative relationship between radioactive contamination and land price.

We exploit the information on the number of transactions in each geographic area to correct for potential sample selection bias. If the reduction in transactions truncates the error distribution of the land price hedonic equation from below, the mean of the error terms should be higher in the area where we observe more significant reductions in transactions because only properties not severely damaged will be transacted. We correct for this sample selection bias based on Heckman (1979)'s method. We do not, however, have micro level observations with the characteristics of the land that would be transacted in the absence of radioactive contamination. We instead observe the reduction of transactions at the geographic group level and apply the sample selection correction method used in the context of group estimators by Blundell, Duncan and Meghir (1998).

The specific procedure for sample selection correction is as follows. First, we construct the fraction of the number of transactions after a year of the accident to the number of transactions before a year in the region j, and denote it as L_j. Second, this L_j is regressed on the natural log of the degree of radioactive contamination $\ln Z_j$ and the regional average of land characteristics $\bar{X}_j$ to obtain the predicted value $\hat{L}_j$ using weighted least squares, with the number of transactions in the pre-accident period as the weight. Third, the mean of the error term of the selection equation, conditional on selection, is constructed as $\frac{\phi(\Phi^{-1}(\hat{L}_j)}{\Phi(\Phi^{-1}(\hat{L}_j))}$, assuming the section equation at each potential transaction has a probit structure. Fourth, this inverse Mill's ratio is added to equation (1) to correct for a potential selection bias. Fifth, the standard errors of the estimated coefficients are calculated based on the bootstrapping of 500 repetitions to reflect the multi-step estimation. In this procedure, we use $\hat{L}_j$ instead of L_j to reduce the effect of sampling errors, particularly for small geographic units. In case $\hat{L}_j > 1$, we assign $\hat{L}_j = 1$, assuming no sample selection. The inverse mill's function is a decreasing function of $\hat{L}_j$, with $\lim_{\hat{L}_j \to 0} \frac{\phi(\Phi^{-1}(\hat{L}_j)}{\Phi(\Phi^{-1}(\hat{L}_j))} = \infty$ and $\lim_{\hat{L}_j \to 1} \frac{\phi(\Phi^{-1}(\hat{L}_j)}{\Phi(\Phi^{-1}(\hat{L}_j))} = 0$. This relationship implies that a significant reduction in transactions results in a high mean value for the error term of the selection equation, or an inverse Mill's ratio. This high inverse Mill's ratio should be positively correlated with the error term of the hedonic price equation if heavily damaged land is not transacted, because only lands with high error terms are transacted in a heavily contaminated area.

Column (1) of Table 4 reports the ordinary least squares (OLS) estimation result with the inverse Mill's ratio. The coefficient for the inverse Mill's ratio is positive, as expected, but not statistically different from zero at a reasonable significance level. Contrary to our prior expectations, the estimated coefficient for the contamination attenuates in Column (2) compared to the coefficient in Column (1). The statistical insignificance of the inverse Mill's ratio suggests the absence of sample selection bias under the limited assumption. This finding seems to suggest that properties within a similarly contaminated area are randomly transacted. While we believe we did the best to deal with the potential sample selection bias with available data, we do not take this as definitive evidence for the absence of sample selection bias. Therefore, we still note a potential attenuation bias because of sample selection as a caveat.

B. Measurement error in radioactive contamination

The measurement of radioactive contamination is based on the airborne survey. We believe such a survey gives the best available measure of radioactive contamination over a wide area, but the degree of contamination is subject to measurement errors. The degree of radioactive contamination is estimated on the basis of the amount of radiation measured by a helicopter at about 300 meters above ground, covering an area with a radius of 600 meters. The distance between the trajectories of the airborne surveys is about 1800 meters, and the degree of contamination in the area not directly covered by the survey is interpolated based on a model. The measurement of radioactive contamination necessarily suffers from errors because of the errors in radiation measurement and model specification. The measurement error is arguably classical, in the sense that it is not correlated with the actual degree of contamination.

We use an alternative measure of radioactive contamination to correct the potential bias of the OLS estimator due to measurement errors. The alternative measure is the designation "priority contamination survey area" alloted to municipalities by the Ministry of Environment for the purpose of planning and implementation of decontamination. By February 2012, the Ministry of Environment had designated 104 municipalities that included areas with radiation of 0.23 micro Sv per hour as priority contamination survey areas (*Osen Jyokyo Jyuten Chosa Tiiki*).[4] The designation of a municipality as priority contamination survey area is a binary indicator corresponding to the degree of radioactive contamination. We consider this binary indicator as an alternative measure of radioactive contamination of a region and use the variable as an instrumental variable (IV) for the continuous variable "Cesium 134/137 mBq/m^2." If the misclassification of "decontamination special area" is orthogonal to the measurement error of "Cesium 134/137 mBq/m^2," the IV estimator is a consistent estimator.

The IV estimates are reported in Column (3) of Table 4. The first-stage F-statistic is above 50,000, confirming a very strong partial correlation of IV and the

[4]The designation is based on various measurements of radiation, including the land surveys implemented by local municipalities, and the MEXT's airborne survey used in this study. The Ministry of Environment also designated 11 "decontamination special areas (Josen Tokubetsu Tiiki)," but all these areas also belonged to the evacuation zone (Keikai Kuiki), or the planned evacuation zones (Keikakuteki Hinan Kuiki), where no property transactions have taken place.

degree of radioactive contamination. The coefficient for Cesium 134/137 mBq/m^2 becomes larger in absolute value. The single-variable Hausman test rejects the null hypothesis of the OLS estimates reported in Column (1), and the IV estimates reported in Column (3) are statistically identical to the Hausman statistics, at about -124 ($= [-0.023 - (-0.029)]/[0.008^2 - 0.007^2]$).

The change in estimated coefficients allows for two interpretations. The first interpretation is that there is an attenuation bias in the OLS estimate reported in Column (1) because of a classical measurement error in radioactive contamination. According to this interpretation, about 21% of the variance in the measured contamination consists of measurement errors, because the OLS estimate is attenuated by 21% compared to the IV estimate.

The second interpretation is based on the local average treatment effect interpretation. The IV estimate is defined as a partial correlation between land price and the designation as priority contamination survey area divided by the partial correlation between the measured contamination and the designation. If the designation as priority contamination survey area has a more negative impact on transaction prices than the impact predicted by the continuous measurement of the contamination, then the IV estimate becomes larger than the OLS estimate.

While both interpretations are possible, attributing the entire difference to measurement error seems to imply implausibly large measurement errors, although the second interpretation is plausible given the stigma attached to the area designated as priority contamination survey area. Since we are interested in the overall effect of radioactive contamination rather than the effect of a possible social stigma, we consider the OLS estimate to be more preferable to study the impact of radioactive contamination on land value over a wide range of radioactive contamination.

C. Correlation with other damages from the East Japan Earthquake

The Great East Japan Earthquake and the subsequent tsunami, the direct cause of the failure of the Fukushima Daiichi plant, caused the land prices to decrease through damages other than radioactive contamination, such as the destruction of infrastructure or flooding. We would be overestimating the damages caused by radioactive contamination if the damages caused by other reasons are correlated with the degree of radioactive contamination. The random distribution of radioactive fallout following the meteorological conditions after the accident ensured that the degree of this potential bias is minimal, but we assess the degree of bias by estimating models that allow for differential price changes by geographic units. We specifically consider prefectures and coastal regions as geographic units that approximate the damages caused by the East Japan Earthquake and the subsequent tsunami. We capture these damages by adding prefectural and coastal region dummy variables that interact with time dummy variables.

Column (4) of Table 4 reports the results with the interaction terms of the prefecture and time dummy variables. These interaction terms naturally capture some variation of radioactive contamination across locations, and this attenuates the coefficient for the contamination variable by 20%, while it inflates the associated standard error by 50%, from the basic specification reported in Column (1). Regardless of these changes, the estimated coefficient is still statistically significant at the 10% significance level.

Column (5) of Table 4 reports the regression results with the interaction terms of coastal region and time dummy variables. In this specification, the coefficient for the contamination variable increases in its absolute value from the result in Column (1), and the associated standard error does not change. The contaminated area is not necessarily concentrated in the coastal area, as shown in Figure 1. Given that the coastal regions are less likely to be contaminated, controlling for the potential damage caused by the tsunami by the coastal region dummy variable increases the baseline land price of non-contaminated areas and enlarges the price differentials between the contaminated and non-contaminated land.

The robustness checks in this subsection confirm the robustness of the result of the basic specification reported in Column (1). While there is a range of estimates based on specifications, we take the estimate of the basic model as the benchmark.

V. Estimates for total land damage

How large is the total damage of the Fukushima accident on residential land? We estimate the total damage of the accident based on the estimated effect of the radioactive contamination on residential land price. Specifically, we calculate the total residential land damage in a municipality, i, by the following formula:

$$D_i = \sum_{r=1}^{9} \bar{P}_i \times \hat{\beta}_1 \times \Delta \ln(Cesium134/137mBq/m^2)_r \times S_{ri} \times A_i, \tag{2}$$

where $\bar{P}_i$ is the average residential land transaction price in municipality i before the accident, $\hat{\beta}_1$ is the estimated elasticity of land price to the radioactive contamination reported in Column (1) of Table 4, $\Delta \ln(Cesium134/137mBq/m^2)_r$ is the change in radioactive contamination in the contamination category r, S_{ri} is the share of residential area contaminated by degree r in the total residential land area in region i, and A_i is the total taxable residential land area in municipality i. From the "Abstract report of fixed property prices (*Kotei shisan no kakaku tou no gaiyo chosho*)," we obtain the total taxable residential land area in each municipality. We calculate the total damage by aggregating the damage estimated for each municipality.

Table 5 reports the results of damage calculation aggregated at the prefectural level for all the 10 prefectures. The total residential land value of the 10 prefectures in the pre-accident period was 491.39 trillion yen and the radioactive contamination decreased the value by 2.65 trillion yen, and thus the devaluation is 0.54% of the original value. The total damage of 2.65 trillion yen is equivalent

Table 5—: Estimated residential land damage by prefecture in trillion yen

	Total Land Value	Estimated Damage	Percentage of Decline
Total	491.39	2.65	0.54%
Iwate	7.27	0.03	0.40%
Miyagi	12.78	0.09	0.71%
Fukushima	9.86	0.67	6.84%
Ibaraki	16.01	0.29	1.82%
Tochigi	12.32	0.11	0.86%
Gunma	11.69	0.21	1.76%
Saitama	60.31	0.06	0.11%
Chiba	50.07	0.96	1.92%
Tokyo	207.94	0.23	0.11%
Kanagawa	103.15	0.00	0.00%

0.56% of Japan's nominal GDP of 2011, that is, 471 trillion yen.

Geographically speaking, we observe the largest damage in the Chiba prefecture, 0.96 trillion yen, followed by the Fukushima prefecture, 0.67 trillion yen. The damage in Chiba accounts for as much as 36% of the total damage. Fukushima prefecture suffers most from the accident in terms of percentage decline, but Chiba prefecture suffers most in terms of total damage. The higher initial residential land price in the Chiba prefecture as compared to the Fukushima prefecture makes Chiba's damage larger, while the degree of contamination in the Chiba prefecture is much lower than that in the Fukushima prefecture. The western part of Chiba prefecture is a commuting area for Tokyo's office workers and hence its residential land value is high. The area around Kashiwa city, a 40-minute train ride from the center of Tokyo, was heavily contaminated by the combination of radioactive plumes and rainfall on March 21, 2011, in spite of the fact that the city is about 200 km south of the Fukushima Daiichi accident site. An important lesson to be learnt from this episode is that valuable land can be damaged by radioactive fallout even if it is remotely located, because radioactive plumes can travel a long distance.

Table 6—: The effects of contamination category on ln residential land price

Dependent Variable: Transaction price: 10 thousand yen per square meter

	(1)	(2)	(3)	(4)
Rank of contamination × after				
30-100 kBq	-0.064	-0.060	-0.060	-0.074
	(0.024)	(0.025)	(0.028)	(0.024)
100-600 kBq	-0.126	-0.116	-0.206	-0.141
	(0.042)	(0.048)	(0.066)	(0.044)
Inverse Mill's ratio	N	Y	N	N
Time F.E.	Y	Y	Y	Y
District F.E.	Y	Y	Y	Y
Time × prefecture F.E.	N	N	Y	N
Time × coastal district F.E.	N	N	N	Y
Observations		59,618		

VI. Functional relationship between contamination and land price

Our estimations heretofore assume a functional form relationship between radioactive contamination and residential land price. While a log–log specification is preferred by the specification test, our damage estimates could change depending on the functional form. To check the robustness of our results, we allow for a more flexible functional form relationship between radioactive contamination and residential land damage by using dummy variables to represent the categories of radioactive contamination. An examination of Table 2 reveals that only a few transactions took place in the analysis period in the area contaminated by more than 600 kBq. Hence, we drop the observations from the heavily contaminated area from the analysis sample. Furthermore, an examination of Table 3 reveals that the residential land price fell by around 10% in the area contaminated by 60 to 600 kBq. We create a dummy variable to represent this level of contamination. We also create another dummy variable to capture the level of contamination between 10 and 60 kBq. We estimate Equation (1) with these two dummy variables in place of the continuous measure of contamination level.

Table 6 tabulates the regression results of several model specifications. Column

(1) reports the base line results, Column (2) gives the results with Heckman sample selection correction, Column (3) allows for prefecture $\times$ time fixed effects, and Column (4) allows for coastal area dummy variable $\times$ time fixed effects. From the base line model reported in Column (1), a contamination by 30–100 kBq reduces the residential land price by 6.4%, and a contamination by 100–600 kBq reduces it by 12.6%. Correcting for a potential sample selection bias does not change the results much, as reported in Column (2). Adding the prefecture $\times$ time fixed effects signifies the impact of contamination by 100–600 kBq, as reported in Column (3). This change of result implies that severe contamination and the unobserved time-varying prefecture effects were positively correlated in the specifications in Columns (1) and (2). This could be perhaps because the area not contaminated by radioactive substances becomes relatively scarce within a prefecture where vast areas of land are contaminated. We consider this as the market equilibrium effect induced by radioactive fallout and thus partialing out this effect is not appropriate for the purpose of cost calculation. Finally, Column (4) indicates that allowing for differential price changes in coastal areas does not change the estimation results.

We treat the results in Column (1) of Table 6 as the most preferred estimates and calculate the total residential land damage based on this specification. Table 7 reports the estimated damage based on Equation (2). According to this specification, the total damage caused is 2.19 trillion yen, instead of 2.65 trillion yen as obtained under log–log specification, corresponding to 0.46% of GDP. The largest estimated total damage is observed in Fukushima prefecture, instead of Chiba prefecture, under the log–log specification, but the damage estimated for Chiba prefecture continues to be ranked second and significant.

In sum, the total damage caused by the Fukushima Daiichi accident is estimated to be around 2.5 trillion yen or 0.5% of Japan's GDP across all specifications. Furthermore, while it is often overlooked, significant damage is observed in not only the neighborhood of the failed plant but also in a remote Tokyo suburban

Table 7—: Alternative estimated residential land damage by prefecture in trillion yen

	Total Land Value	Estimated Damage	Percentage of Decline
Total	491.39	2.19	0.45%
Iwate	7.27	0.01	0.14%
Miyagi	12.78	0.05	0.35%
Fukushima	9.86	0.80	8.07%
Ibaraki	16.01	0.22	1.38%
Tochigi	12.32	0.10	0.81%
Gunma	11.69	0.21	1.80%
Saitama	60.31	0.03	0.05%
Chiba	50.07	0.74	1.48%
Tokyo	207.94	0.04	0.02%
Kanagawa	103.15	0.00	0.00%

area, the Chiba prefecture, where residential land price before the accident was high.

VII. Change in effects of proximity to nuclear power plants

There are several reasons other than radioactive contamination as to why proximity to nuclear power plants depreciates residential land prices after the Fukushima Daiichi accident. A straightforward reason would be the change in risk assessment; the accident might have updated the damage estimate due to plant failure and might have depreciated the residential land price near nuclear power plants. While Fink and Stratmann (2013) did not find changes in residential land prices near nuclear power plants in the United States, given the significant media attention to the damage caused by the radioactive contamination around Fukushima, consumers in Japan might have responded differently.

Another more significant indirect effect would be the change in local economic activities and the consequent land price depreciation; the accident activated national debate on the safety regulation on the operation of nuclear power plants. All nuclear power plants were shut down for scheduled inspections after the accident and proposals to restart them had to undergo a more strict review process by the Nuclear Regulation Authority, newly established in September 2012, and strong political opposition at central and local government levels.[5] These two factors have made restarting the nuclear power plants difficult, and, as of September 2014, none of the 48 reactors of 17 plants are in operation and 9 reactors are scheduled to be decommissioned. Local economies where the nuclear power plants are located typically depend heavily on the plant operation for employment and tax revenue (Ando (2015)). The shutdown of nuclear power plants therefore negatively affects the local economic activities in a significant way and may have reduced the residential land value. Indeed, Bauer, Braun and Kvasnicka (2013) found that the decrease in housing prices near nuclear power plants in Germany was mainly because people expect a lowering of economic activities in the area in response to the government's decision to abolish nuclear power generation in the long run.

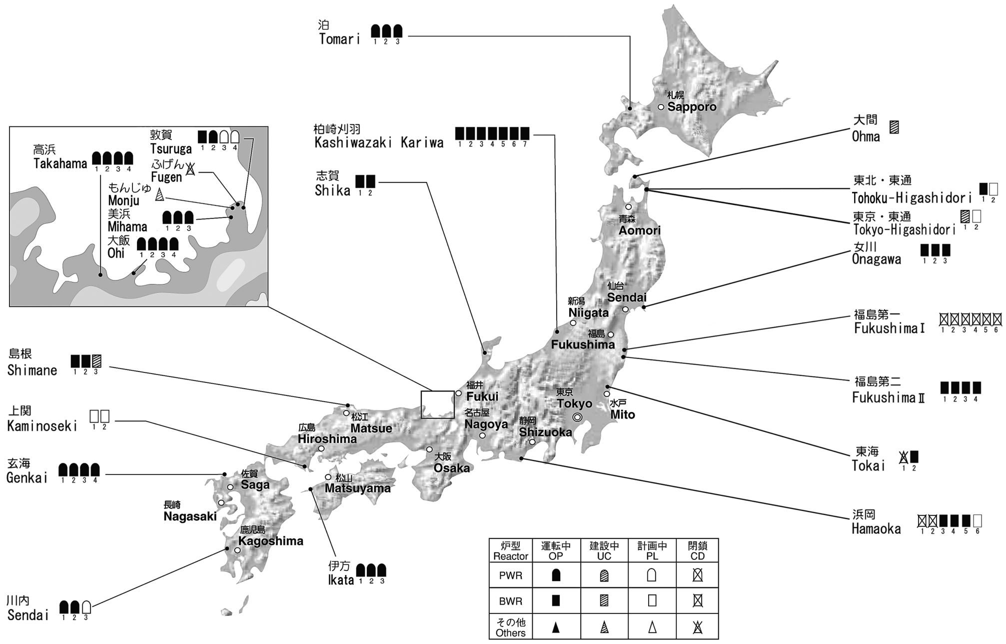
It is extremely difficult to distinguish the effects of proximity to a nuclear power plant from the effects of radioactive contamination on residential land price by using only Fukushima data because proximity to the accident site and the degree of contamination co-vary closely. To overcome this difficulty, we consider data on residential land transactions around two nuclear power plants located reasonably close to Fukushima accident site but not directly affected by radioactive contamination. The two nuclear power plants are Higashidori in Aomori prefecture and Kashiwazaki-Kariwa in Niigata prefecture (Figure 2).[6]

Consistent with the previous analysis, we download all residential land transactions without housing units that took place between the second quarter of 2010 and the first quarter of 2012. The total number of transactions is around 2,300

[5]Until September 2012, the operation of nuclear power plants had been regulated by the Nuclear and Industrial Safety Agency, a part of the Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry. This regulatory system had been criticized because the regulatory body is not independent from the Agency in charge of energy policy including the promotion of nuclear power generation. In response to this criticism, the Japanese government established the Nuclear Regulation Authority as an affiliated agency to the Ministry of Environment so that the safety regulation could be implemented independent from the energy policy.

[6]Onagawa nuclear power plant in Miyagi prefecture could be a candidate for this exercise, but we did not use Onagawa plant because the area was contaminated by radioactive fallout from Fukushima Daiichi.

Figure 2. : Locations of nuclear power plants



Source: Japan Atomic Industrial Forum, Inc.

for Aomori and 5,500 for Niigata. We estimate the following equation using this data set.

$$\ln p_{ijt} = \beta_0 + \beta_1 w_t \cdot \ln dist_j + x_{it}\gamma + c_j + d_t + f_{jt} + u_{ijt}, \tag{3}$$

where p_{ijt} is the price per square meter, w_t is the dummy variable for post-accident period, $dist_j$ is the distance of city j's city hall from nuclear power plants, x_{ij} is the vector of land characteristics, c_j is the land fixed effects (558 units in Aomori and 1,512 in Niigata), d_t is the year-quarter fixed effects, f_{jt} is the uncorrelated region-time heterogeneity, and u_{ijt} is the unobserved idiosyncratic effect. Note that the effect of w_t is absorbed in d_t and $dist_j$ in c_j. If the proximity to nuclear power plants reduces residential land prices, we should expect $\beta_1 > 0$.

In Table 8, Panel A tabulates the result with pooled data, Panel B tabulates the results with Aomori prefecture data, and Panel C tabulates the results with

Table 8—: Change in residential land prices depending on the distance from nuclear power plants

Dependent Variable: Transaction price: 10 thousand yen per square meter

Panel A: Aomori and Niigata Prefectures			
	(1)	(2)	(3)
ln (distance from nuclear plant) × After	0.019	0.016	0.052
	(0.031)	(0.042)	(0.093)
Inverse Mill's ratio	N	Y	N
Time F.E.	Y	Y	Y
District F.E.	Y	Y	Y
Time × coastal district F.E.	N	N	Y
Observations		7,743	
Panel B: Aomori Prefecture			
	(1)	(2)	(3)
ln (distance from nuclear plant) × After	-0.012	-0.062	0.263
	(0.098)	(0.138)	(0.320)
Inverse Mill's ratio	N	Y	N
Time F.E.	Y	Y	Y
District F.E.	Y	Y	Y
Time × coastal district F.E.	N	N	Y
Observations		2,288	
Panel C: Niigata Prefecture			
	(1)	(2)	(3)
ln (distance from nuclear plant) × After	0.027	0.029	0.014
	(0.033)	(0.082)	(0.107)
Inverse Mill's ratio	N	Y	N
Time F.E.	Y	Y	Y
District F.E.	Y	Y	Y
Time × coastal district F.E.	N	N	Y
Observations		5,455	

Niigata prefecture data. The estimated coefficients are in the range between 0.016 and 0.052 except for Panel B, and none of the estimated coefficients is statistically different from zero. These results indicate that the change in price of residential land does not depend on the distance from nuclear power plants. This result suggests that the residential land price depreciation around the Fukushima Daiichi accident site is most probably because of radioactive fallout, rather than proximity to the nuclear power plant.

VIII. Conclusion

We estimated the total damage on residential land caused by the Fukushima Daiichi nuclear power plant accident from the real estate transactions data covering the period before and after the accident, matched with airborne survey results on radioactive contamination. We used a hedonic price equation with detailed geographic unit fixed-effects and found that radioactive contamination significantly depreciates residential land value. The estimated total damage ranges from 2.19 to 2.65 trillion yen, that is, about 0.5% of Japan's GDP. The damage in the Tokyo metropolitan area makes up a significant part of the total damage.

This study has three important limitations. First, our damage estimate does not cover the area designated as the official evacuation area. The investigation committee on the finance and management of the Tokyo Electric Power Company estimates the total property damage of the evacuated area to be 570.7 billion yen, including land, buildings, depreciable assets, and automobiles. Second, our analysis period covers only up to one year after the accident. The long-term evolution of price reaction is an important future research topic because people's risk perception on radioactive contamination may change over time. Third, our analysis is limited to the damage on residential land. The damage on agricultural land could also be substantial; however, the study of this subject is not easy because the simple capitalization hypothesis does not seem to apply to agricultural land transaction prices because of regulations on the transactions (Keiji and Hiroshi

(2008)). The total damage estimated in this study should be interpreted with these three caveats.

There could be a gap between how people perceive the health risk of radioactive contamination and its actual effect on health outcomes. In addressing this important question, linking the residential land price change with the actual change in health outcomes, such as infant mortality or birth weight, as done by Currie et al. (2013), is also an important future research topic.

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