Flood Protection and Land Value Creation

Not All Resilience Investments Are Created Equal

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Abstract

This paper investigates the land value creation potential from flood mitigation investments in a theoretical and applied setting, using the urban area of Buenos Aires as a case study. It contributes to the literature on the wider economic benefits of government interventions and the dividends of resilience investments. Using a simple urban economics framework that represents land and housing markets, it finds that not all flood mitigation interventions display the same potential for land value creation: where land is more valuable (city centers for example), the benefits of resilience are higher. The paper also provides ranges for land value creation potential from the flood mitigation works in Buenos Aires under various model specifications.

Although the estimates vary largely depending on model parameters and specifications, in many cases the land value creation would be sufficient to justify the investments. This result is robust even in the closed city configuration with conservative flood damage estimates, providing that the parameters remain reasonably close to the values obtained from the calibration. Finally, acknowledging that fully calibrating and running an urban simulation model is data greedy and time intensive—even a simple model as proposed here—this research also proposes reduced form expressions that can provide approximations for land value creation from flood mitigation investments and can be used in operational contexts.

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1 Introduction

Cost-benefit analyses of projects aiming at reducing flood risks traditionally consider benefits in the form of avoided loss of life and capital destruction, while the costs consist of the investment and maintenance spending of the project. There is a strong suspicion however that the benefits of urban resilience projects at large and in particular those focusing on urban floods are underestimated. The triple dividend framework (Tanner et al. 2015), for example, makes the case that besides the reduced costs from floods (1st dividend), Disaster Risk Management (DRM) interventions can unlock economic potential through the reduction in background risk (2nd dividend) and allow for possible development co-benefits (3rd dividend), such as shelters doubling as community spaces. Whether we consider the triple dividend framework or other closely linked terminologies such as "wider economic benefits" or "secondary benefits" of resilience, the notion that benefits from disaster risk management interventions go beyond avoided losses is gaining traction with both economists and practitioners alike. It opens the possibility of addressing (some of) the shortcomings of traditional Cost-Benefit Analyses while also potentially providing a better assessment of the value of various DRM interventions.

The second dividend in particular relies on the reduction of the background risk which can encourage more investments and less risk averse behaviors, both of which are central to economic development. In particular, in urban settings subject to floods, the risk reduction enabled by the DRM project can promote more investments in the flood prone area in the form of more or better housing and business development. For example, in an area flooded annually but located close to many jobs, some households may decide that the benefits of accessible jobs outweigh the costs of the floods. They would then choose to settle there but will be unlikely to invest much in their dwellings and well-being given annual capital destructions. If the flood risk disappears (or is drastically reduced) because of better flood protection, many more households are likely to choose to settle in the area and will invest more in their dwellings as the damages would be lower.

The reduction in risks is captured through land value appreciations when land markets are functional. Estimates suggest that measures such as canal improvements, storm and wastewater upgrades aiming at reducing flood impacts can lead to land value appreciations in the range of 11% - 18% (OECD 2011). This opens up the possibility of land value capture from the authorities in order either to pay for the costs of the resilience project or to finance other public priorities. This benefit should be captured in Cost-Benefit analyses.

But local land value creation from resilience investments is not the same thing as land value creation in the urban area. Indeed, reduction in flood risks, will, at the scale of the urban area change the relative attractiveness of land plots, so that while the newly protected areas will see an increase in attractiveness (translated into higher land values) others will see a decrease. To some extent, by protecting some areas from natural disasters and changing the relative attractiveness of locations within the urban area, resilience investments will trigger a transfer in land values across space.[1] Whether these transfers lead to an aggregate increase in land values in the urban area, and if so of what magnitude, is a more complex question. But the aggregate net effect is precisely the question of interest for urban planners and city

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[1] This redistribution of land values across the urban area carries potential consequences for various administrative levels if they rely on land value taxes for own source revenues. We acknowledge that this is an important consideration but choose in this paper to focus only on the net aggregate impact of flood mitigation works.

officials hoping to leverage land value creation for fiscal purposes or for recovering part of the resilience investment costs.

Much has been written on the topic of land value creation and capture linked to urban transport investments both to quantify the effects of increased accessibility on land and property values (Arnott and Stiglitz 1979; 1981; Stokenberga 2014; Viguié and Hallegatte 2014; Gupta, Van Nieuwerburgh, and Kontokosta 2020) and to discuss practical ways in which public authorities can recuperate part of these appreciations through fiscal means (Suzuki et al. 2015; Medda 2012; Peterson 2008; Germán and Bernstein 2018). In comparison, despite an increased interest in the "wider economic benefits" of government interventions (World Bank 2018), and with a few notable exceptions (Grafakos et al. 2019; Smolka 2013), relatively little is known about the potential for disaster risk management investments to create land value appreciation and ultimately to create fiscal space for local governments. This research contributes to filling this gap by focusing on the potential for land value creation from flood mitigation works in urban areas.

We use a simple applied urban economics model (NEDUM-2D) to investigate land value creation from flood mitigation investments (Viguié and Hallegatte 2012; Viguié, Hallegatte, and Rozenberg 2014). This methodology has several advantages. First, because we rely on a simulation model, we can conduct assessments ex-ante, without having to wait until the completion of the investments and the adjustments of land markets to measure and provide estimates of potential land value creation. This is important as one of the objectives of this research is to provide tools that can be used to perform enhanced Cost-Benefit Analyses which are typically required at the project design phase (for example for World Bank project appraisals). Second, such a simulation model captures some of the general equilibrium effects of interventions in the urban area and can document not only the local land value appreciations but also the transfer of land values across locations. As such it provides a more complete picture than hedonic evaluations. We do not argue that this methodology is a substitute to data collection and empirical studies to measure land value creation from resilience investments – in fact, it would be important to confront our ex-ante estimates with on-the-ground measurements in the future – rather that it is a useful complement.

Our main results show (1) that the location of floods in the urban area matter for the potential for land value creation from flood risk mitigation investments, (2) land value creation depends on the amount of in-migration triggered by increased resilience and improved living standards; and the model provides a range using two extreme modeling assumptions: the closed or open city settings, (3) that relaxing housing regulations in association to flood mitigation investments does not necessarily translate into increased land value creation, (4) that while land value creation estimates vary widely depending on modeling choices, in most cases, they are either superior to, or represent a significant share (33% or more) of, the initial flood mitigation investments. This is true even in the closed city configuration with conservative flood damage estimates, providing that the parameters remain reasonably close to the values obtained from our calibration. This demonstrates the importance of accounting for land value creation in Cost-Benefit Analyses.

The paper is structured as follows. To illustrate the dynamics at play, Section 2 introduces a perfectly circular schematic urban economics model and investigates the impacts of floods and flood mitigation on aggregate land values and household utilities in open and closed cities under different land ownership assumptions and by varying the locations of flood-prone areas. Section 3 briefly introduces the NEDUM-

2D model and documents its application on the urban area of Buenos Aires. It also details the flooding information used in this study and how it is integrated into the simulation model. Section 4 presents the results in terms of avoided damages and potential land value creation from flood mitigation investments in Buenos Aires combined or not with housing regulation relaxation. Section 5 presents a reduced form expression that can be used to approximate the potential land value creation estimates from the fully calibrated NEDUM-2D model. Section 6 relies on Decision Making under Deep Uncertainty techniques to test the robustness of our central results to changes in modeling parameters and data interpretation. Finally, section 7 discusses this research effort, provides avenues for future work and concludes.

2   Resilience investments and land value creation in a simple model

2.1   A simple urban economics model accounting for floods

2.1.1   Modeling Principles

In this section, we present the principal features and equations of the standard urban economic modeling framework that accounts for floods. We do so briefly, because the basic urban economic model has been extensively described in many papers and books (e.g., (Brueckner 2011; Fujita 1989)) and the introduction of floods in the framework leads to only marginal changes. We use a model inspired by von Thünen (1826), adapted by Alonso (1964), Mills (1967), and Muth (1969) and comprehensively described in Fujita (1989). Assuming that a city is defined by a number of jobs located in a single location, the CBD, this static model is based on two trades-offs, made by two categories of economic actors, and together they characterize a static equilibrium in the urban system:

- Households choose their housing location in the agglomeration by arbitrating between larger and cheaper dwellings further from the city center, and increased commuting costs to the city center where all jobs are assumed to be located.

- Landowners choose where and how much to invest (i.e., what buildings to construct), as a function of expected rents at each location.

2.1.2   Households

Each household is composed of one representative worker living at a distance r from the city business district (CBD) where all jobs are located. Each worker has to commute once a day to the CBD, and this commuting entails transportation costs $T(r)$. All households are supposed to earn the same income Y and – at the equilibrium – they have the same level of satisfaction described by a utility function U that depends on both the level of consumption of a composite good z and of the size of their dwelling q. The level of rents per square meter (or, equivalently, the annualized real estate price per square meter) is $R(r)$, at each location in the city. Each household maximizes his or her utility function under the budget constraint described in (1) by choosing where to settle in the urban area r, where r is the distance to the CBD, how much housing space q to consume and what to spend on other goods z. The term $\bar{L}$ represents the annual amount accruing from land rents per household which is recycled in the urban economy in the form of increased incomes.

$$Max_{r,z,q} \ U(z,q) \qquad s.t. \quad z + R(r)q + T(r) \leq Y + \bar{L} \qquad \qquad (1)$$

2.1.3   Developers and landowners

Developers purchase land from landowners at price $P(r)$, and in doing so incur an annual opportunity cost of capital iP, i, being the real interest rate. Developers first decide whether to allocate land to agricultural purposes or to housing. In the first case their revenue is $R_a L$, where R_a is the agricultural rent and L the area of land they own. In the second case, they choose what amount of capital $K(r)$ to invest at each distance from the CBD to produce a housing surface $H(r)$. In this framework, they are thus also the owners of the buildings. The amount of floor space built and the annual land rents depend on an exogenous specific construction technology which displays constant returns to scale but diminishing returns to capital: $H(r) = F(K(r), L(r))$. These decreasing returns to capital will cap the building heights and as consequence the total amount of residential floor space. Developers will only invest large amounts of capital to build tall buildings when the anticipated rents $R(r)$ they expect will offset the extra building costs. The edge of the city is given by an exogenous and constant agricultural rent R_a below which it is no longer profitable to build. At the edge of the city (r_f) we therefore have $R(r_f) = R_a$.

$$\pi(r) = [R(r)F(K(r), L(r)) - \left(i + \rho + \rho_{f_j}\right)K(r) - iP(r)] \tag{2}$$

Under the classic assumption of zero-profit condition for developers, which supposes a competitive construction market, the price of land is given by equation (3):

$$P(r) = \frac{1}{i}[R(r)F(K(r), L(r)) - \left(i + \rho + \rho_{f_j}\right)K(r)] \tag{3}$$

Developers maximize their profit function (2), which consists in identifying the optimal amount of capital to invest at each location (4):

$$K(r) = Argmax[R(r)F(L(r), K(r)) - \left(i + \rho + \rho_{f_j}\right)K(r)] \tag{4}$$

The term ρ represents the joined effect of real-estate depreciation and annual taxes paid by landowners on real-estate capital. i is the real interest rate so that iK represents the annual opportunity cost of capital.

The parameter ρ_{f_j} expresses the damage to structures caused by floods at location j in the city. It is comprised between 0, when location j is not hit by floods, and 1. The cost of floods is expressed as the capital destroyed when floods hit, or, alternatively, as the capital needed to repair the structure to its pre-flood condition. In this model, the only impact of floods is through capital destruction. All other consequences (e.g., casualties and fatalities) are disregarded, assuming they can be avoided with relevant tools, e.g., early warning and evacuation. These damages from floods depend on the location in the urban area and are not necessarily identical everywhere. They are in turn the result of two factors, the damage caused by floods in location j when these happen, δ_j, and the return period of the flood, τ_j, with the return period of flood typically ranging from frequent annual events to much more exceptional events occurring every 100 years or more, such that:

$$\rho_{f_j} = \frac{\delta_j}{\tau_j} \tag{5}$$

The term $\bar{L}$ found in (1) can schematically take on one of two values depending on the type of model used: city models with Absentee landowners or city models with public ownership of land. In the city models with absentee landowners, landowners are supposed to live outside the urban area which means that land rents are not recycled in the local economy in the form of increased incomes. In this case $\bar{L} = 0$. At the opposite end of the spectra, if all land plots are supposed to be owned by a local government (or by all households in equal shares) then $\bar{L} = \int_0^{r_f} \frac{P(r)}{N} dr$, where N is the number of households in the urban area.

2.1.4   Functional forms and further assumptions

We use Cobb-Douglas functional forms with constant returns to define households' utility and the housing service construction function, a choice that is widely shared in urban economics[2]:

$$U(z,q) = z^\alpha q^\beta \ \ where \ \alpha, \beta > 0 \ and \ \alpha + \beta = 1 \tag{6}$$

$$F(L,K) = AL^a K^b \ where \ a, b > 0 \ and \ a + b = 1 \tag{7}$$

We also make the following additional simplifying assumptions for sections 2.2 and 2.3 but lift them in subsequent sections:

- Transport costs increase linearly with distance from the city center, $T(r) = p * r$, where p is the generalized cost of transportation including the cost of time.
- The agricultural rent R_a is supposed to be null. This simplification is not necessary but it makes most of the calculations much easier without altering results.
- At each distance r from the city center, and assuming a perfectly circular city, we can define the available land as the following increasing function of r: $L(r) = lr$ where $l=2\pi$.

2.2   Locations of floods impact household utility and aggregate land values

Figure 1 shows household utility and aggregate land values in various schematic cities where floods occur in comparison to an equally schematic city but where floods are absent. Although the cities presented here are unrealistic because they assume no land and housing regulations and constraints and rely on linear transport costs, they use realistic parameter values that are calibrated so as to reproduce the main features of the urban area of Buenos Aires (see sections 6 and the Appendix). The eight cities represented in Figure 1 differ by the location of the floods: spread across the city (a, b), localized in one quadrant but

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[2] The appropriate functional form for the housing construction function has been widely debated in the literature with some scholars arguing that a CES with a substitution elasticity between capital and land inputs below one is a better fit because capital to land ratios increase at a slower rate than land prices (Larson and Yezer 2015). However, measuring land values and invested capital appropriately is uneasy and creates empirical challenges which are likely to bias estimates of the substitution elasticity downward. Works that have paid closer attention to this measurement problem tend to find much higher substitution elasticities and ones that are very close to 1, meaning that Cobb-Douglas functions, although not perfect, are an appropriate representation for housing production functions (Thorsnes 1997; Epple, Gordon, and Sieg 2010; Ahlfeldt and McMillen 2014; Combes, Duranton, and Gobillon 2021).

proportional to the distance to the city center (c, d), localized in the periphery (e, f) or localized in central areas (g, h). They also differ by the severity of the floods, with the left column showing in dark grey unmitigated floods destroying 20% of the structures located in flood prone areas (a, c, e, g), and the right column showing mitigated floods in light grey that destroy 10% of the structures located in flood prone areas. It should be noted that the area affected by floods in all localized flood scenarios (c to h subplots) is identical at 25% of the urbanized area, so that differences in household utility and aggregate land values can only be explained by the location of floods and their severity; not the total flood-prone area.

A number of conclusions can be drawn from this figure. The results in terms of household utility and aggregate land values are shown for one specific setting, namely the Closed City with Public ownership of land (CCP). In this setting, the population is exogenous and unaffected by damage caused by floods, i.e. increased or reduced floods are assumed not to affect migration to and from other parts of the country. In parallel, it is assumed that revenues accruing from land rents are entirely recycled into the local economy in the form of a complementary income that each household benefits from in equal shares.

First, household utility is unambiguously reduced when floods are present compared to a "no-flood" situation. But the magnitude of the decrease depends on the severity of the flood and the location of the flood-prone areas. The more severe the flood, the lower the household utility for a given distribution of flood-prone areas. This can be explained by higher construction costs linked to having to maintain or replace structures, which leads to higher rents. The loss in household utility is highest when floods affect the whole city. The loss of utility is also very large when floods are located in the central parts of the urban area. For localized floods that affect only peripheral areas or one quadrant of the city, household utility losses are lower.

Second, aggregate land values are unaffected by floods when these are distributed homogeneously throughout the urban area (a, b) or proportionally to the distance to the city center (c, d). This result is consistent with Avner and Hallegatte (2019), that show, with Cobb-Douglas functions, that higher structure depreciation rates caused by the costs of floods (or risk-based insurance) lead to a decrease in built housing surface that is exactly compensated by higher rents, leaving landowners' profits unaffected. In other terms, flood losses are fully transferred to tenants.
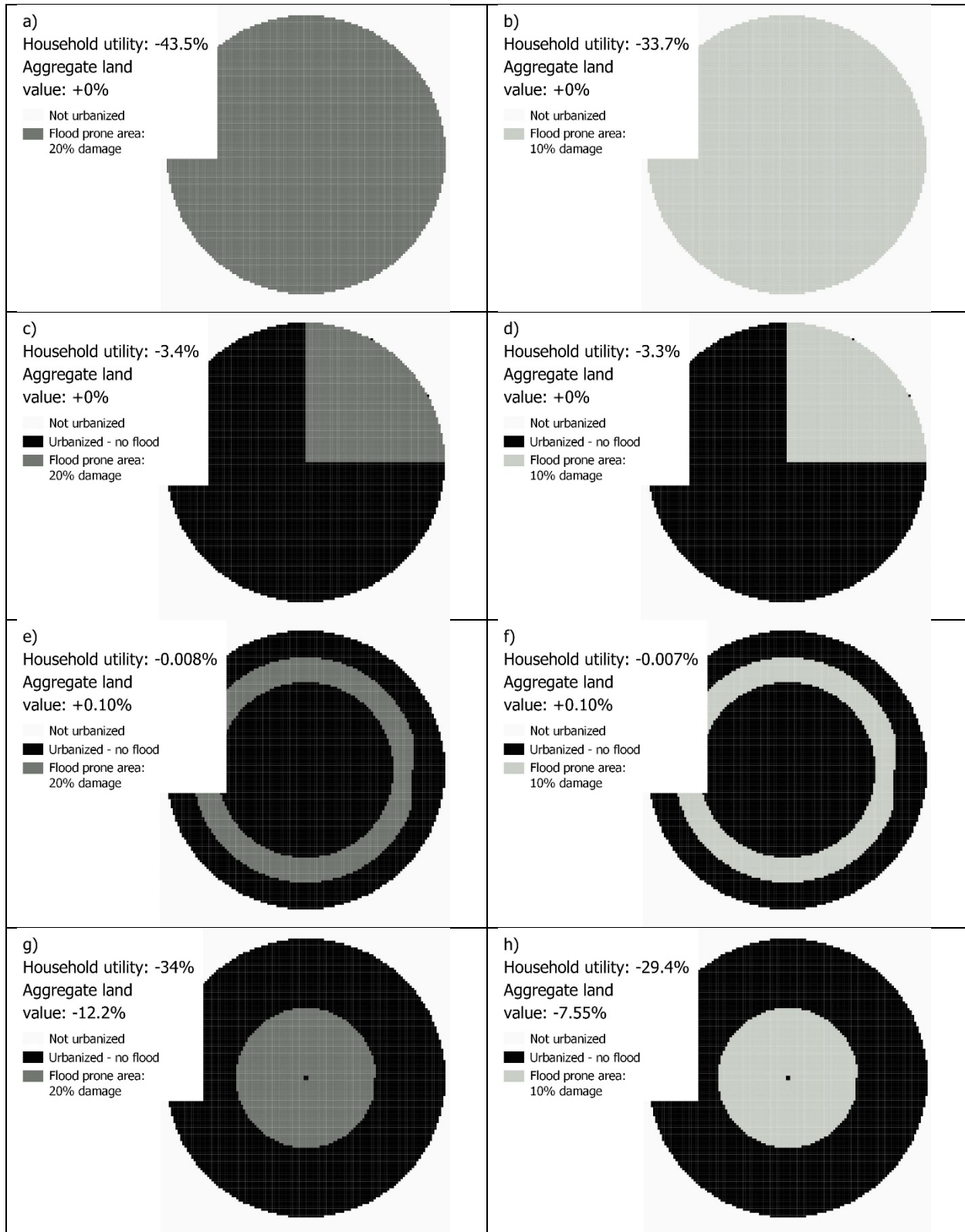
Figure 1: Household utility and aggregate land value impacts of floods compared to a no-flood situation depending on the location of flood prone areas and the severity of floods (damage inflicted to structures when a flood occurs). The left column represents floods that are more severe and destroy 20% of the structures. The right column represents floods that are less severe and destroy

Thirdly, aggregate land values are impacted in different ways when floods are localized in a specific part of the city. When flood-prone areas are peripheral (e, f), aggregate land value are shown to increase slightly (+0.102% - +0.099%). When flood-prone areas are central (g, h), aggregate land values decrease significantly (-12.2% - -7.56%) compared to a "no-flood" situation. The reason behind this is that in a closed city framework, as is the case here, the population of the urban area is fixed and makes locational decisions by trading-off localized housing rents and transport costs under the constraint of housing supply that depend on landowners' profit maximization. Where floods occur, the supply of housing space is more limited because the costs of constructions are higher. So that when floods are in the periphery, households cannot enjoy as large dwellings as they would do in the absence of floods and consequently some of them choose to move closer to the city center, making this area, which already displays higher land values, more attractive, triggering an absolute increase in aggregate land values in the city. There is a transfer of land values from the periphery to the center. When floods are central, the opposite happens. Landowners and developers will build less in the most valuable central areas, and more in the periphery, therefore triggering a redeployment of the population and a transfer of land values toward less valuable lands. The net effect is a decrease in aggregate land values. This result is important because it shows that floods have complex effects on land values. On one side, floods have the aggregate effect of reducing housing supply which leads to higher rents and tends to inflate land values. On the other hand, lower localized supply of housing leads to a new locational trade-off for households which will choose to settle elsewhere in the urban area and potentially in lower value places, which would tend to depreciate land values. The net effect depends on the location of the floods.

Lastly, and linked to the previous conclusion, mitigating the frequency or the damage caused by urban floods, for example through public interventions aiming to achieve resilience will have opposite impacts on aggregate land values depending on the location of the floods. When floods are in the periphery, decreasing their severity, they will also decrease aggregate land values. This can be seen from aggregate land values going from +0.102% to +0.099% compared to a "no-flood" situation in figures e) and f). Arguably the effect remains small. Conversely, mitigating central floods, will make the most valuable parts of the city's land more attractive again, thereby leading to an increase in aggregate land values: from -12.23% to -7.56% compared to a "no-flood" situation in subplots g) and h) of Figure 1. This result is key as it frames the possibility of creating land values from investing in resilience: not all risk reduction investments create value in aggregate (although, locally, it is true). Those that protect the most valuable land in urban areas will create land value in a closed city setting.

2.3   How are the results affected in open city settings or with absentee landowners?

The results in section 2.2 were derived in a specific setting of classic urban economics – namely a Closed City with Public ownership of land (CCP). But how are these results affected in the other three main urban economics settings – Closed City with Absentee landowners (CCA), Open City with Public ownership of land (OCP) and Open City with Absentee landowners (OCA).? The absentee landlords' assumption means that land rents are not recycled into the urban economy and do not accrue in the form of increased incomes to local residents, $\bar{L} = 0$ in equation (1). The Open City's assumptions means that the urban national system is interdependent, such that any pressure upwards or downwards on household utility

will result in in- or out- migration respectively such that all households in any city of the system display the same utility level at any given time: $u = \bar{u}$; whereas the population N, becomes endogenous.

When flood prone areas are distributed proportionally to the distance from the city center (configurations a) to d) in Figure 1), it is possible to show analytically, using Cobb-Douglas functions and building on Avner and Hallegatte (2019), how household utility (u), aggregate land values (ALV) and city populations (N) are affected by floods compared to a no-flood situation in all four polar city configurations (CCA, CCP, OCA and OCP).

	Closed Cities	Open Cities
	CCA	OCA
Absentee Landowners	$\begin{cases} u_{f_{CCA}} = C_f^{\frac{1}{\gamma}} * u_{N_{CCA}} \\ ALV_{f_{CCA}} = ALV_{N_{CCA}} \\ N_{f_{CCA}} = N_{N_{CCA}} = \bar{N} \end{cases}$	$\begin{cases} u_{f_{OCA}} = u_{N_{OCA}} = \bar{u} \\ ALV_{f_{CCA}} = C_f * ALV_{N_{CCA}} \\ N_{f_{OCA}} = C_f * N_{N_{OCA}} \end{cases}$
	CCP	OCP
Public Ownership of Land	$\begin{cases} u_{f_{CCP}} = C_f^{\frac{1}{\gamma}} * u_{N_{CCP}} \\ ALV_{f_{CCP}} = ALV_{N_{CCP}} \\ N_{f_{CCP}} = N_{N_{CCP}} = \bar{N} \end{cases}$	$\begin{cases} u_{f_{OCP}} = u_{N_{OCP}} = \bar{u} \\ ALV_{f_{OCP}} = C_f * ALV_{N_{OCP}} \\ N_{f_{OCP}} = C_f * N_{N_{OCP}} \end{cases}$

Table 1: Household utility (u), Aggregate land values (ALV), and city population (N) when floods affect a city compared to a no-flood situation in the four classic urban configurations (open or closed cities with absentee landowners or public ownership of land) when flood-prone areas are proportional to the distance to the city center, corresponding to cases a), b), c and d) in Figure 1.

C_f and γ in Table 1 are parameters that intervene in calculations with $C_f = (1 - \theta) + \theta \left(\frac{\rho+i}{\rho+i+\rho_f} \right)^{\frac{b}{a}}$, with ρ_f being identical over all flood-prone areas (there is only one flood type) and $\gamma = \frac{1}{a\beta}$.

In closed cities (CCA and CCP), two results, already reported in Avner and Hallegatte (2019), are noteworthy. First, household utility is decreased by a factor $C_f^{\frac{1}{\gamma}}<1$, compared to a 'no-flood' situation, translating the fact that reduced housing supply will increase unitary housing rents and lower housing consumption, all else equal. Second, Aggregate land values (ALV) remain at their 'no-flood' level as the decrease in housing supply and increase in housing construction costs are exactly compensated by higher housing rents. This result, documented in section 2.2, is true in the CCA situation also.

In open cities (OCA and OCP), household utility is exogenously given such that it is equal in flooded or non-flooded settings. However, city population will adjust through in- or out-migration in order for household utility to remain constant. Two results here are also noteworthy. First, both population and aggregate land values are decreased by a factor $C_f < 1$, with homogenously distributed flood-prone areas, compared to a no-flood situation in both OCA and OCP settings. It should be noted that $C_f > C_f^{\frac{1}{\gamma}}$, so that the decrease in population and aggregate land values is higher in open cities than the decrease in utility in closed cities. Second, aggregate land values per household remain at their 'no-flood' level, such that $\bar{L}_{f_{OCP}} = \bar{L}_{N_{OCP}} = \bar{L}_{N_{CCP}} = \bar{L}_{f_{CCP}}$.

When floods are central or peripheral, analytic calculations are more difficult to derive. We use simulations informed by the same set of parameters as in section 2.2 and described in section 6 and the

Appendix to provide estimates of how floods affect household utility, aggregate land values and populations compared to a no flood city, when floods are not necessarily distributed proportionally to the distance to the city center (Table 2).

		Cities							
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Household utility	CCA	-43.5	-33.7	-3.4	-3.3	-0.001	-0.001	-32.3	-28.4
	CCP	-43.5	-33.7	-3.4	-3.3	-0.008	-0.007	-34.0	-29.4
	OCA	0	0	0	0	0	0	0	0
	OCP	0	0	0	0	0	0	0	0
Aggregate land values	CCA	0	0	0	0	+0.008	+0.008	-10.2	-6.22
	CCP	0	0	0	0	+0.10	+0.10	-12.2	-7.55
	OCA	-99.1	-96.7	-24.8	-24.2	-0.004	-0.003	-96.5	-94.2
	OCP	-99.1	-96.7	-24.8	-24.2	+0.038	+0.037	-97.2	-94.9
Population	CCA	0	0	0	0	0	0	0	0
	CCP	0	0	0	0	0	0	0	0
	OCA	-99.1	-96.7	-24.8	-24.2	-0.012	-0.012	-96.1	-93.8
	OCP	-99.1	-96.7	-24.8	-24.2	-0.063	-0.062	-96.9	-94.5

Table 2: Household utility, aggregate land values and population variation (in %) compared to a no-flood situation depending on the location of flood prone areas and the severity of floods (damage inflicted to structures when a flood occurs) in the four polar settings of classic urban economics.

For closed cities, impacts from floods for household utility losses and aggregate land values compared to a 'no-flood' baseline are identical between CCA and CCP models when floods are homogenously distributed in the urban area (cities (a) to (d)).[3] And results for floods which are distributed in the city center or in the periphery are very similar in CCA and CCP models for utilities and aggregate land values (cities (e) to (h)). For open cities, the same conclusions hold between OCA and OCP models: identical impacts on land values and populations for cities (a) to (d) and very similar results for these same variables when floods are central or peripheral (cities (e) to (f)).

This suggests that the absentee landowner or public ownership of land assumption has limited impacts on our results. One small exception here consists of the results for aggregate land values in OCA and OCP models when floods are peripheral (cities (e) and (f)). Whereas the impacts of floods on aggregate land values are nearly non-existent in both cases, the sign of the change is different: negative, meaning aggregate land value destruction from floods in an OCA setting, positive, meaning aggregate land value creation in an OCP setting.

The difference in impacts from floods are much more significant between open or closed city models. First, because utility is fixed in open city models, populations decrease with floods, leading to much less severe competition for land and smaller aggregate land values. This is true even when floods are homogenously distributed (cities (a) to (d)) where no impacts are reported in closed cities. For these cities ((a) to (d)), the loss of utility in closed cities is measured by $C_f^{\frac{1}{\gamma}} = C_f^{a\beta}$, whereas the loss of population and aggregate land values is measured by C_f in open cities. With both $a < 1$ and $\beta < 1$, $a\beta$ is small

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[3] Note that this is distinct from saying that household utilities are identical in cities with Absentee Landowners or Public Ownership of land: they aren't. But they are reduced in the same proportion when compared to their 'no-flood' situations, which constitute distinct baselines in CCA and CCP models.

(0.3x0.4=0.12 with our set of parameters), implying that $C_f^{\frac{1}{\gamma}}$ is much closer to 1 than C_f. This means that the impacts of floods on aggregate land values is much higher in open city settings when population can adjust through in- or out-migration than in closed city settings when population is fixed.

3   Application to Buenos Aires

3.1   NEDUM-2D model and application to the urban area of Buenos Aires[4]

We use the NEDUM-2D model (Viguié and Hallegatte 2012; Viguié, Hallegatte, and Rozenberg 2014) to investigate the implications of flood mitigation investments on land values in the urban area of Buenos Aires. NEDUM-2D (Non-Equilibrium Dynamic Urban Model) is an extension of the standard monocentric[5] urban economic model with one income group[6] such as defined by Fujita (1989) but informed with real world data such as transportation times. We have already introduced its main principles, features, equations as well as assumptions in section 2.1 so we will focus here briefly on how it departs from the one-dimensional traditional model, what data we provide it with for real-world city applications and how it performs in reproducing observations, in this case on Buenos Aires.

The version of NEDUM-2D we use in this analysis differs from the standard model developed in Fujita (1989) for two main reasons. First, the theoretical model described by Fujita (1989) represents spatial differences solely as a function of the distance to the city center. As the name suggests NEDUM-2D is two-dimensional meaning that it is an urban model that represents urbanization on a map rather than on a single axis. NEDUM-2D uses a grid with cells of variable size (classically 1km² or 500mx500m). It can therefore account for spatial differences in land use and accessibility at a much finer scale. The model can represent differences between two cells situated at the same distance from the city center such as the amount of land that can be built upon, land use features and topological constraints such as parks or rivers, or measured transportation times and costs.

Second, the classic urban economy model only represents one means of transport. In NEDUM-2D there are three main transport options: private cars, public transport and walking. For each location in the urban area, citizens choose between walking, public transport and private vehicles, or a combination of these as a means for commuting. The competition between these modes is organized on the basis of their *generalized costs* (i.e. the total cost including both the cost of time and the monetary costs incurred during the trip to the city center). It is assumed in this study that modal switch does not affect congestion levels and therefore leaves commuting times unchanged. In order to reflect the heterogeneity of citizens' preferences in terms of transport modes we employ a discrete choice model (De Palma and Thisse 1987).

With a limited amount of data describing the size of the population, households' average income, the transport systems summarized by generalized transport costs to reach the CBD for each mode at the grid cell level, land use including areas that cannot be built, housing regulations such as FARs, construction costs, households and developers' behavior, the NEDUM-2D model can reproduce the structure of Buenos

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[4] Some of the following paragraphs in section 3.1 describing the NEDUM-2D model appear in a similar form in Avner et al. (2017). For the purposes of making this paper self-standing, it was deemed important to include them here as well.

[5] This mono-centric hypothesis is a clear simplification but that finds some support in the data for the specific case of Buenos Aires, the Buenos Aires region displays a strong mono-centric structure. For instance, in 2012 more than 40% of all jobs in the Buenos Aires region are localized in the *Ciudad Autónoma de Buenos Aires* (CABA) even though CABA only represents 5.3% of *Region Metropolitana*'s area.

[6] For a version of NEDUM-2D that represents multiple job centers and household types differing by annual average income and work location see Pfeiffer et al. (2019).

Aires in a convincing way.[7] For this exercise we rely on the data collection and processing as well as the calibration efforts undertaken for a previous study on the Buenos Aires area (Avner et al. 2017). The interested reader will find the main calibration and validation details in the Appendix and a complete documentation, including data descriptions and modeling choices, is available in the main text and appendices of Avner et al. (2017). The previous study is however enriched by a number of features such as the use of a higher resolution grid (500mx500m), the multiple city configurations studied (Open or Closed cities, public ownership of land or absentee landowners), and the introduction of flood damages (see section 3.2).
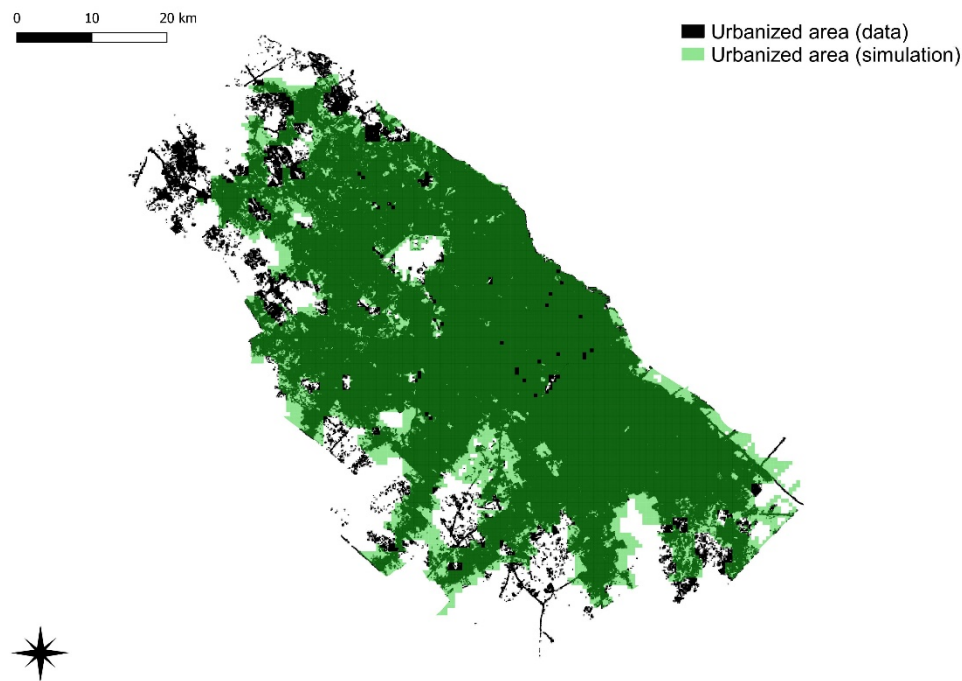
Figure 2: The simulated and real urban area of the GBA+ region in 2012. The green shade corresponds to the simulation whilst the black is geographic data. The dark green shade shows areas where the model accurately predicts urbanization. Light green shows areas where the model inaccurately predicts urbanization. Black stands for areas where the model fails to reproduce urbanization. Finally, where the map is white, there is no urbanization and the model agrees with the data.

Figure 2 provides one element of the model validation; more validation information is presented in the Appendix. It shows that the simulated and the actual urban area in 2012 coincide well within the larger Greater Buenos Aires region (which is called GBA+, in black in the figure). The model captures the general size of urbanized area but also its shape and specific urbanization directions along the transportation network. There are however some discrepancies even within the GBA+ boundaries. In particular it can be seen that the map misses some areas towards the North and the North West of the GBA+ region. This can mainly be explained either by the existence of local secondary employment centers that attract settlements or the presence of local amenities.

3.2   Flood data and damages before and after resilience investments

The flood hazard maps used in this analysis were produced by the Government of Buenos Aires in 2018 as part of their *Plan Director de Ordinamiento Hidráulico* (PDOH) or watershed management plan. The

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[7] The model has been successfully applied to the urban area of Paris (Viguié and Hallegatte 2012; Avner, Viguié, and Hallegatte 2013; Avner, Rentschler, and Hallegatte 2014; Viguié, Hallegatte, and Rozenberg 2014), London (Viguié 2012), Buenos Aires (Avner et al. 2017), Toulouse (Masson et al. 2014) and Cape Town (Pfeiffer et al. 2019).

flood hazard maps, corresponding to the Cildáñez, Maldonado and Vega basins, cover an area which is slightly larger than the *Ciudad Autonoma de Buenos Aires* (CABA) or city of Buenos Aires proper and, therefore not the whole area of study which corresponds to the *Area Metropolitana de Buenos Aires* (AMBA). It should be noted here that our study focuses on floods that occur mostly in CABA, a vastly smaller area than our area of study. There are two sets of flood maps: before and after works planned in the PDOH, aiming to reduce flood instances. The works planned to mitigate flooding consist mostly of stormwater drainage and retention capacity investments in the three water basins. In both cases a flood hazard map (in polygon form) is produced that provides the extent of a flood for a given return period and for a given flood depth. Return periods range from frequent events occurring every two years to rare events occurring once every 100 years. The list of return periods considered is the following: 2, 5, 10, 20, 50 and 100 years. Flood depths range from 15 centimeters to 160 centimeters. The full list of flood depths considered is: 15, 25, 40, 90 and 160 centimeters. In total, with each flood map being produced after flood protection works and in their absence, there are 59 flood maps.[8] Typically, the area covered by a given flood-depth for a specific flood return period is smaller after flood mitigation actions have been implemented.

Each flood map is intersected (overlayed) with a grid that has homogenous 500m x 500m sized grid cells so that the flooded share of land, $s_{j,\tau,d,w}$, of each grid cell (j), is known for each of the 59 flood maps, depending on the return period of the flood (τ), the depth of the flood (d) and whether flood protection works have taken place or not (w). Given that for a given grid cell, a given return period and a given public works scenario, the share of land flooded by 160 centimeters, is also by construction flooded by 15 centimeters of water, there is some obvious double counting of flooded areas that needs to be addressed. In a geometric sense, areas that are only flooded by 15 centimeters of water (not more) constitute the outer concentric ring of areas which are also flooded by 25 centimeters of water, by 40 centimeters and so on[9] (see Figure 3 for a visual representation of flood maps for a centennial event before flood mitigation investments). We address this double counting by defining $s\_ring_{j,\tau,d,w}$ as follows:

$$s\_ring_{j,\tau,d,w} = \begin{cases} s_{j,\tau,d,w} - s_{j,\tau,d+1,w} & for\ d \in \{15, 25, 40, 90\} \\ s_{j,\tau,d,w} & for\ d = 160 \end{cases} \qquad (8)$$

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[8] We would expect 60 distinct flood maps for each flood depth, return period and in the absence or after flood protection works: 5x6x2=60. However, after flood protection works, there are no locations that get flooded every two years with a water depth of 160 centimeters, therefore we have 59 flood maps rather than 60.

[9] This pattern has some very limited exceptions: out of the sum of 10,699 instances where a grid cell is impacted by a specific flood event (before resilience investments), only in 97 of these do we observe unusual behaviors where a bigger flood-depth is not contained within the area of a smaller flood-depth for any given return periods. We also find that out of the 961 grid cells that get flooded in part or in whole by at least one flood event (before flood mitigation), in only 31 of these does the flood data show bigger flood depth areas that are larger than smaller flood depths. These localized discrepancies can possibly be explained by some small errors in the hydrological modeling or the transcription of these results into shapefiles. We deal with these outliers by assuming that a concentric ring for a smaller flood-depth cannot have a negative value: $s_{j,\tau,d,w} \geq s_{j,\tau,d+1,w}$.
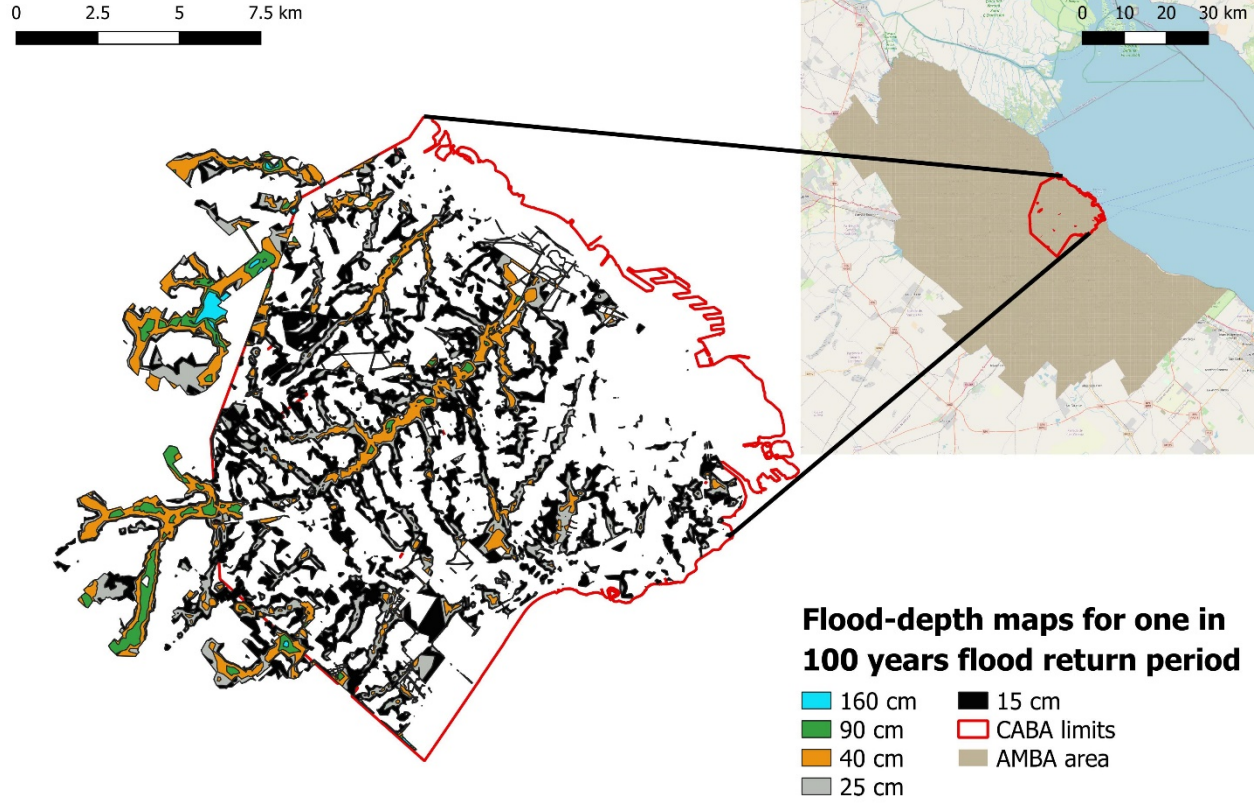
Figure 3: Flood maps for the one in a hundred-year return period flood event before resilience investments.

The total damage of floods at the grid cell level expressed in terms of percentage of the (re)construction costs can be expressed through the flood depreciation factor ρ_f, which accounts for the share of land in each pixel j which is flood prone as well as the frequency of the flood τ, and the damage δ_d inflicted to buildings which are flooded, as a function of flood depth[10]:

$$\rho_{f_{j,w}} = \frac{1}{100} * \sum_d s_{ring_{j,\tau=100,d,w}} * \delta_d + \sum_{\tau=2}^{50} \left(\frac{1}{\tau_i} - \frac{1}{\tau_{i+1}}\right) \sum_d s_{ring_{j,\tau_i,d,w}} * \delta_d, for \ \tau \ \in \{2,5,10,20,50,100\}$$

The missing piece is interpreting damages in percentage of reconstruction costs as a function of flood depths δ_d. For this we rely on flood depth-damage curves reported by two studies, 1) Hallegatte et al. (2013) based on Huang (2005) and 2) Englhardt et al. (2019), linearly interpolating the damages they report as a function of flood depth to match the flood-depth data we have. There is considerable uncertainty in assessing how floods and water depth affect structures (Jongman et al. 2012) and the two studies we use reflect this, with a large spread in values for a given flood depth (see Figure 4). In both

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[10] The expression of $\rho_{f_{j,w}}$ will result in a lower bound estimate of the costs of floods on structures because, in the absence of good information on the form of the function linking damages and flood return periods, we do not fully integrate the area below the damage curve function. Making the assumption that damages increase linearly with flood return periods would allow us to perform a complete integration of damages but would undoubtedly overestimate the costs of floods.

cases we retain for our study the estimates that concern the sturdiest type of building material[11] (category 'masonry' in Hallegatte et al. (2013) and category VIb, corresponding to two-story residential structures constructed with reinforced masonry or steel, in Englhardt et al. (2019)) and yet for a 1m50 water depth, structural damage is estimated at around 8% and 38% respectively. We choose to rely on the flood damage estimates derived from Hallegatte et al. (2013) for our central scenario, as this is less likely to overestimate the benefits from flood protection investments, but we also show aggregate results derived by using the estimates from Englhardt et al. (2019). With these assumptions we have defined a depreciation rate linked to flood occurrences at the pixel level, depending on flood protection investments, $\rho_{f\,j,w}$. We can now turn to the results of the model in terms of land value creation triggered by resilience investments.
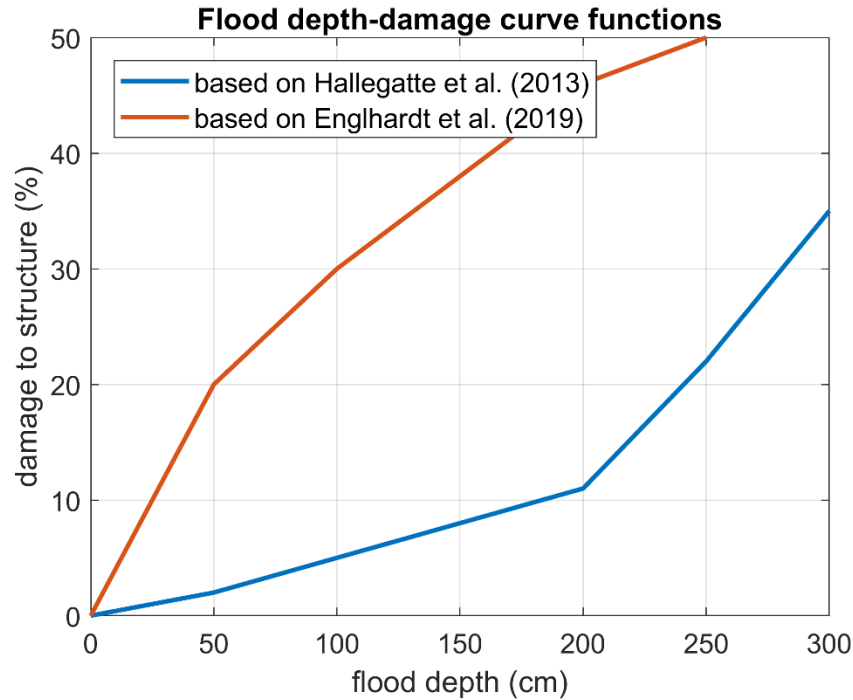

Figure 4: Flood depth-damage curve functions based on two different studies (Hallegatte et al. 2013; Englhardt et al. 2019)

4   Results

4.1   Potential land value creation in closed and open cities

As discussed in section 2.2, the assumption about land ownership (Absentee landowners or Public ownership of land) in the urban area has limited impacts on the results of our simulations focusing on the potential for land value creation linked to resilience investments. On the contrary the assumption of open or closed city models has important implications. For this reason we choose to present our results for the

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[11] We choose 'masonry' damage as the appropriate estimate of damages to buildings. As the floods occur in the central part of the urban area of Buenos Aires, it is reasonable to assume that most structures are built from solid materials (such as reinforced concrete) and engineered. With lower quality housing (built from timber for example), floods increase the damages as a function of the initial building costs. This estimate is however conservative as we disregard the damages to the contents of dwellings.

CCP and OCP settings only, in our central scenario using lower bounds flood damage estimates, as there is some evidence that housing ownership rates are high in Buenos Aires (Fay 2005).
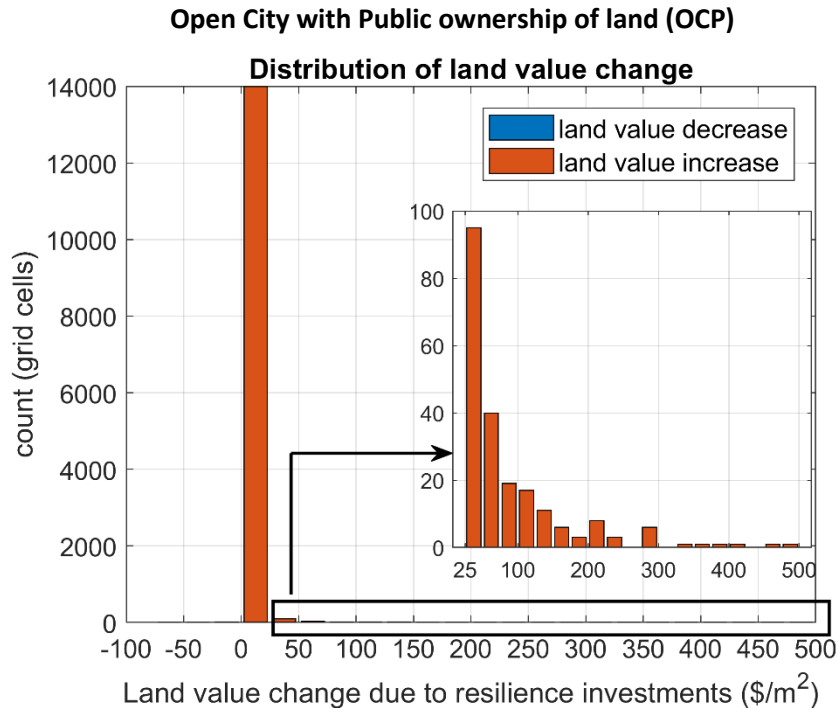
Figure 5 shows the distribution of land value changes triggered by the flood protection investments in both CCP and OCP settings in our central exercise where we use flood depth-damage estimates from Hallegatte et al. (2013). While in both cases, the mean land value change is positive, 0.29$/m^2 for CCP and 1.74$/m^2 for OCP, signaling aggregate land value creation, the pattern of change is vastly different across both cities.

In the closed city model, more than 95% of grid cells (13,704 out of 14,465) see their land value decrease as a response to the resilience investments. Only 3.3% of grid cells (473) see an increase and the remaining 238 are unaffected. There is a vast transfer of land values toward areas that benefit from increased resilience to floods from the rest of the urban area. While the average increase in land value per m^2 is large (39.94$/m^2), the average decrease is mild (-1.07$/m^2). The top histogram of Figure 5 in particular, demonstrates the importance of accounting for land and housing market equilibrium effects. The positive variation in land values amounts to US$ 2.19 billion according to our central estimations in a CCP setting. The corresponding negative variation in land values is close to US$ -1.81 billion. The actual land value creation is the difference between these two amounts: US$ 379 million. Ignoring the land value transfer/destruction linked to land and housing market adjustments would vastly overestimate the aggregate land value appreciation in the urban area (US$ 2.19 billion vs US$ 379 million). These results strongly support the use of equilibrium models rather than hedonic pricing strategies when the objective is to understand aggregate land value changes from investments rather than purely local ones.

In the open city model, conversely, only 20 out of 14,465 grid cells (0.14%) experience a decrease in land value, while grid cells that show an increase in land values represent 98% of the urban area. The average increase in land value is much smaller than in the closed city case (+1.78$/m2) but spread across a much wider area, while the average decrease in land values is much higher (-7.25$/m2) for a limited number of grid cells.

Closed City with Public ownership of land (CCP)

Distribution of land value change
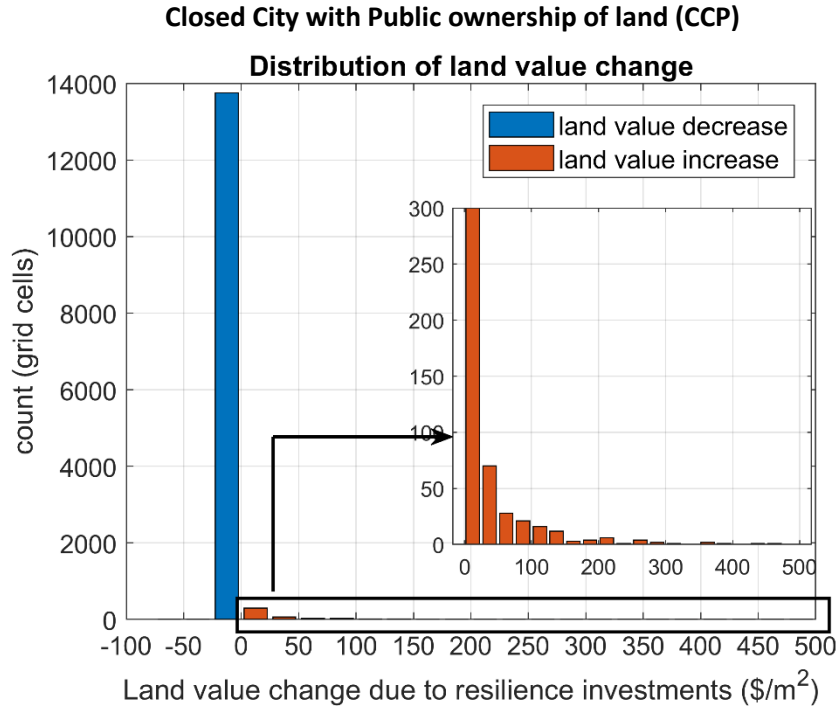
Note: The maximum land value decrease is -44.2$/m², the maximum increase is +471.5$/m², the median change is -0.22$/m² while the mean is 0.29$/m².

Open City with Public ownership of land (OCP)

Distribution of land value change

Note: The maximum land value decrease is -40.1$/m², the maximum increase is +483.5$/m², the median change is +0.07$/m² while the mean is 1.74$/m².

Figure 5: Distribution of land value changes due to resilience investments in CCP (top) and OCP (bottom) settings

Table 3 shows the impact of flood protection investments on aggregate land values, household utility and population size in both the CCP and the OCP setting and for two flood depth-damage curves; the lower

bound one retained for our central scenario that relies on Hallegatte et al. (2013) and the alternative higher bound one that uses the findings from Englhardt et al. (2019).

In total, as shown in Table 3, aggregate land values increase in both the CCP and OCP settings. For our central scenario using lower bound damage estimates, aggregate land values increase by 0.10% and 0.79% respectively. With our central baseline calibration parameters,[12] this translates into net land value creations of US $0.38 and $2.94 billion respectively. Using higher bound damage estimates, the increases in land values are much higher, +0.48% and +4.57% in the CCP and OCP settings respectively, amounting to US $1.93 and $16.95 billion net land value creation from resilience investments. The large range of these figures shows the importance of the choice of modeling closed or open cities but also of the choice of the flood vulnerability curves. The closed city assumption is more realistic in the short term, but some degree of in-migration due to reduced flood risks, consistent with the open city assumption, could happen in the longer term. In comparison, the flood mitigation works are estimated at US $338 million.[13] This means that the lower bound land value appreciation estimation alone would nearly be able to cover the cost of the resilience investments.

The flood protection investments not only increase aggregate land values, opening up the possibility for land value capture, but are unsurprisingly also welfare improving. In the CCP setting, household utility increases by 0.08% and 0.48% for lower and higher bound flood damage estimates, whereas in the OCP setting the investments trigger an in-migration of approximately 28,000 and 165,000 households (or a 0.68% and 4.01% population increase).

	CCP		OCP	
	Lower bound damage estimates from Hallegatte et al. (2013)	**Higher bound damage estimates from Englhardt et al. (2019)**	**Lower bound damage estimates from Hallegatte et al. (2013)**	**Higher bound damage estimates from Englhardt et al. (2019)**
Aggregate land value change	$379 million	$1,928.7 million	$2,935.8 million	$16,949.3 million
Aggregate land value variation	+0.10%	+0.52%	+0.79%	+4.57%
Household utility variation	+0.08%	+0.48%	0%	0%
Population change	+/- 0 households	+/- 0 households	+27,991 households	+164,742 households
Population variation	0%	0%	+0.68%	+4.01%

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[12] A large sensitivity analysis, using techniques adopted for Decision Making under Uncertainty, is performed on most calibrated parameters of the model to explore the robustness of our results as well as which parameters drive our results. This analysis is documented in section 6. It is shown that parameter b, which intervenes in the construction cost function and the real interest rate i have strong impacts on our results and that land value creation ranges from approximately US$ 6 thousand to US$ 4.5 billion depending on their values (excluding 3 of 3,000 runs that return negative values).

[13] see the project appraisal document of the project:
https://documents.banquemondiale.org/fr/publication/documents-reports/documentdetail/287961468328119648/argentina-flood-risk-management-support-project-for-the-autonomous-city-of-buenos-aires.

4.2   Comparison of land value creation and avoided damages

The NEDUM-2D model can also shed light on the avoided damages from flood protection investments, that is the amount of capital that does not need to be invested to repair structural damages, i.e. restore structure to their pre-flood integrity. To do so we compute the following formula for aggregate avoided damages AAD.

$$AAD = \sum_j (\rho_{f_{j,a}} - \rho_{f_{j,b}})K_{j,b} \tag{9}$$

In equation (9), $\rho_{f_{j,a}}$ and $\rho_{f_{j,b}}$ are the flood depreciation rates after and before the resilience investments respectively for grid cell j, while $K_{j,b}$ is the invested capital in structures in grid cell j before flood mitigation interventions.

The annualized avoided damages from floods in both the closed and open cities with public ownership of land (CCP and OCP) are US$ 47.4 million and US$ 102 million respectively using the Hallegatte et al. (2013) and the Englhardt et al. (2019) flood-depth damage functions. Avoided damages are identical in CCP and OCP settings because we rely on capital investments pre-resilience investments only, $K_{j,b}$, which is by construction identical in the baseline in CCP and OCP settings as we start from CCP's household utility in the baseline scenarios. In comparison, annual land value increases in the CCP settings are US$ 7.6 million and US$ 38.6 million with Hallegatte et al. and Englhardt et al. flood damage functions respectively. Corresponding numbers in the open city setting (OCP) are US$ 58.7 million and US$ 339 million.[14]

In CCP settings net land value creation potentials therefore represent approximately 16% and 20% of avoided damages whereas in OCP settings, that account for in-migration as a result of increased household welfare because of improved resilience to floods, land value creation represents between 124% and 172% of avoided damages, depending again on the flood depth damage curve function selected. As highlighted earlier, the CCP results are more realistic in the short term, but in the long-term some degree of in-migration can be expected as a result of flood mitigation works, consistent with the OCP setting. In all cases, numbers that we derive from land value appreciation with respect to avoided damages are significant but they are especially high in open city settings. If instead of focusing on aggregate land value creation at the scale of the urban area, we look at land value increases only in the areas of the city that benefit directly from resilience investments, where flood damages decrease, we find that local annualized land value increases are always superior to avoided damages.

We conclude this sub-section with a note of caution: whereas it is interesting and useful to compare land value creation potential and avoided damages from flood mitigation works, researchers and cost-benefit practitioners alike should refrain from adding these two benefits as the risk of double-counting is real, with land value increases capturing to a large extent or in full the reduced damages from floods. Exploring what is the correct approach to include these two benefit categories will be the topic of future work.

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[14] The numbers displayed for land value creation in sections 4.1 and 4.2 differ because section 4.1 reports land value creation potential for the lifetime of the structure investments whereas section 4.2 reports annual land value creation in order to be comparable with annual avoided damages. Total land value creation is equivalent to annual land value creation divided by the real interest rate, they both entertain a very direct relationship (see equation (3)).

4.3   Impact of relaxing FAR regulations on estimated land value creation

There are Floor-Area Ratio (FAR) regulations in place in the Buenos Aires region, and in particular in the city of Buenos Aires proper (CABA). We account for these in the model by adding a map that provides information about the maximum Floor Area Ratios – the ratio between the maximum amount of space built for residential or other purposes and the land area the structure is built-on – in *CABA* together with the type of use allowed in each zone. We thus limit the maximum height of buildings within *CABA*. We also exclude zones that are uniquely destined to commercial or industrial uses from being urbanized for residential purposes. To do so we intersected our grid with data from the 2011 Código de Planeamiento Urbano (CPU).[15] The CPU map provides for each zone the classification of buildings that can be built. From this information we can retrieve the type of buildings (residential commercial etc.) and the maximum allowed height. For each grid cell we averaged the data to obtain the average building height for residential purposes in *CABA* (Figure 6). Beyond *CABA* however we do not introduce maximum building heights. It should be noted that FARs only have a loose connection to the number of floors that can be built on a given land plot so that equating both is a simplification that is valid for our modeling purposes only. Indeed, a residential FAR of 1, for example, is the ratio between the amount of living space that can be built and the area of a plot of land. This can correspond to one floor if the building occupies the total space of the land plot, two floors if the building occupies only half the land plot area or even 4 floors if it occupies 25% of the land plot.
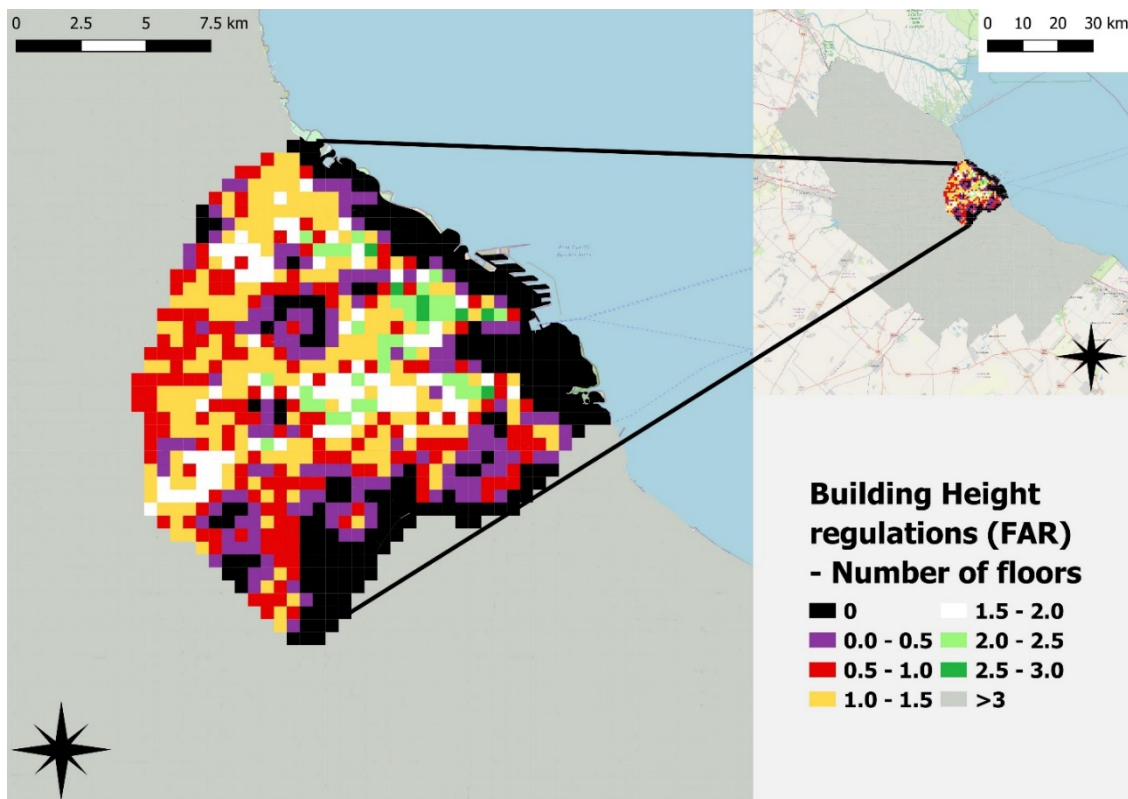

Figure 6: Maximum number of floors for residential purposes in CABA (data source: Código de Planeamiento Urbano - 2011, SSPLAN). Outside CABA, we assume that there are no building regulations.

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[15] Accessible at: http://data.buenosaires.gob.ar/.

The location of floods and flood mitigation investments overlap largely with the area where FAR regulations are present and stringent (i.e. they effectively limit structure heights and purpose). The floods considered in this analysis extend slightly beyond the *Ciudad Autónoma de Buenos Aires* (CABA), where FARs are in place (see Figure 3). From this situation follows an interest in understanding the impacts of the resilience investments associated to the relaxation of FARs. Could this combination result in increased land values created compared to the implementation of flood mitigation strategies alone? And if so, what would the magnitude of this increase be? These questions are also motivated by findings from urban economics that building height regulations can have negative consequences for urbanites' welfare because they cap the supply of available space for housing in valuable locations, thereby increasing housing prices and contributing to urban sprawl (Bertaud and Brueckner 2005; Brueckner and Sridhar 2012; Brueckner et al. 2017; Brueckner and Singh 2020; Glaeser, Gyourko, and Saks 2005).

To investigate this question, we run simple simulations. In the baseline, we assume the current FAR regulation and the current level of flood risks and damages. In the counterfactual scenario, we assume that flood risks are mitigated as described in sections 3.2 and 4.1 but we also increase FARs for residential purposes by 20%, meaning that built housing space is allowed to increase by up to 20% in these specific areas compared to the baseline when these regulations effectively capped housing supply.

Our simulations, with lower bound flood damages, show a number of results. First, as documented in Bertaud and Brueckner (2005) and subsequent papers, household utility increases in a closed city setting (CCP case). With our specification, household utility increases by +0.11% compared to the baseline. This is higher than with flood mitigation investments alone where utility increased by +0.08%, indicating that the combination of resilience investments and the relaxation of stringent building height regulation does indeed achieve welfare improvement which are higher than with resilience investments alone. In an Open City framework (OCP), we find similar results. While household utility is exogenous, population increases by 0.91%, compared to the baseline, when resilience investments and relaxed FARs are combined which is higher than the increase of 0.68% when resilience investments are implemented alone. This demonstrates an increased attractiveness of the urban area of Buenos Aires through an upward pressure on household utility when building height regulations are loosened alongside flood mitigation.

Second, a combined relaxation of FARs and flood mitigation investments have more complex impacts for aggregate land value creation, which depend on the city setting. In the Open City configuration (OCP), aggregate land values are driven by population change and therefore increase with FAR relaxation compared to both the baseline with unmitigated floods and the scenario where floods are mitigated but FARs unchanged (+0.94% compared to +0.79% with resilience investments alone; an increase of nearly US$ 556 million between the two scenarios). In the Closed City configuration (CCP), the combination of FAR relaxation and flood mitigation does indeed result in local land value appreciations in the city center, and to a very limited net aggregate increase in land values compared to the unmitigated flood scenario - +0.01% - at the scale of the urban area. This increase in aggregate land values compared to the unmitigated flood scenario is however lower than in the flood mitigated scenario alone: +0.01% vs 0.1%; in fact, it is one order of magnitude lower. The relaxation of FARs results in an increase of US$ 51 million compared to the unmitigated flood baseline but a loss of more than US$ 327 million compared to a scenario of resilience investments alone.[16] The relaxation of the FARs close to the city center indeed

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[16] Flood mitigation investments and FAR relaxation have opposite impacts on aggregate land values in a closed city setting. Which effect dominates depends on the magnitude of the regulation relaxation and the magnitude of the

encourages more housing construction in these areas, which can result in some local land value increases compared to resilience investments alone (in 475 grid cells or about 3.3% of the total) but in the process it also decreases housing rents (per m²) in the entire urban area, which tend to depreciate land values.

5   Approximating land value creation potential

While the NEDUM-2D model used above is in many aspects a simple urban model, relying only on core urban economics, calibrating, and using it in other urban areas to estimate land value appreciations from resilience might be out of reach of local planning agencies because of lack of data, staff time or the right mix of technical skills. For this reason, we develop in this section a reduced form approximation of localized and aggregate land value changes that relies on a more limited set of data and parameters and can be computed outside of the fully calibrated model.

From equation (3), we have the annual price of land iP:

$$iP(r) = [R(r)F\big(K(r), L(r)\big) - \big(i + \rho + \rho_{f_j}\big)K(r)] \tag{10}$$

With housing density per unit of land, $h = Ak^b$, and $a + b = 1$, landowners' program maximization leads to:

$$k(r) = \left(\frac{R(r)Ab}{\rho + i + \rho_f}\right)^{\frac{1}{a}} \tag{11}$$

which then gives:

$$h(r) = A^{\frac{1}{a}}b^{\frac{b}{a}}\left(\frac{R(r)}{\rho + i + \rho_f}\right)^{\frac{b}{a}} \tag{12}$$

and:

$$iP(r) = R(r)^{\frac{1}{a}}A^{\frac{1}{a}}\left(\frac{1}{\rho + i + \rho_f}\right)^{\frac{b}{a}}(b^{\frac{b}{a}} - b^{\frac{1}{a}}) \tag{13}$$

We can also express the unitary housing rent at each distance from the city center as a function of the unitary housing rent in the most central location of the urban area, R_0.

$$R(r) = R_0 \left(\frac{Y - T(r)}{Y}\right)^{\frac{1}{\beta}} \tag{14}$$

Combining equations (13) and (14), we can express the unitary land value, $P(r)$, as:

$$P(r) = \frac{1}{i}R_0^{\frac{1}{a}}\left(\frac{Y - T(r)}{Y}\right)^{\frac{1}{a\beta}}A^{\frac{1}{a}}\left(\frac{1}{\rho + i + \rho_f}\right)^{\frac{b}{a}}(b^{\frac{b}{a}} - b^{\frac{1}{a}}) \tag{15}$$

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flood damages. In this specific case, FAR relaxation diminishes aggregate land values compared to a scenario in which flood mitigation investments are implemented alone but still increases aggregate land values compared to an unmitigated flood scenario. It is however conceivable that situations could exist in which the FAR relaxation effect is stronger than the flood mitigation impact on land values and where aggregate land values would decrease in comparison to an unmitigated flood scenario.

Let us denote all variables that differ between before and after resilience investments as NR, for "non-resilient", and R, for "resilient" respectively. As transport costs and most parameters are not altered by flood mitigation investments, we can then compare land values in each grid cell P_R and P_{NR} as follows:

$$\frac{P_R}{P_{NR}} = \left(\frac{R_{0_R}}{R_{0_{NR}}}\right)^{\frac{1}{a}} \left(\frac{\rho + i + \rho_{f_{NR}}}{\rho + i + \rho_{f_R}}\right)^{\frac{b}{a}} \tag{16}$$

The second term in equation (16) can easily be interpreted as the fraction of capital costs imposed by floods without flood mitigation works compared to a situation in which flood resilience investments have taken place. It will be equal to one when grid cells are either unaffected by floods or where resilience works do not affect flood depths and ensuing damages, or superior to one when flood mitigation works translate into lower damages and flood depreciation rates. The first term in equation (16) translates the reduction in central housing rents, and equivalently the gains in households' utility, that stem from increased housing supply in valuable locations. This first term will be equal to or lower than one where flood resilience investments have tangible impacts on the housing stock and the relative attractiveness of specific locations in the urban area. Combining the first and the second term, the net impact on localized land values is not straightforward.

Unfortunately, whereas the second term is easy to estimate from the use of flood maps combined with flood depth – damage curve functions, the first term is impossible to compute without relying on a fully fledged urban economics model as we have described and used throughout this study. It however can be proxied for, through several simplifications. We report below how the changes in central housing rents because of resilience investments can be approximated and provide calculation details in the Appendix.

$$\frac{R_{0_R}}{R_{0_{NR}}} \approx 1 + bf_1x_1 + bf_2x_2 + \cdots. \tag{17}$$

In equation (17), f_1, f_2, …, represent fractions of the total urban population living in grid cells 1, 2,…, so that $f_i = \frac{n_i}{N}$, where n_i is the population residing in grid cell i, and N is the total population in the urban area. And x_1, x_2, … represent the difference in flood depreciation parameters divided by the initial complete unitary capital costs, so that $x_i = \frac{\left(\rho_{f_R} - \rho_{f_{NR}}\right)}{\left(\rho_{f_{NR}} + \rho + i\right)}$.

If we combine (16) and (17) and aggregate over the whole urban area, we can compute the ratio of aggregate land values with and without flood mitigation works, ALV_R and ALV_{NR} as:

$$\frac{ALV_R}{ALV_{NR}} \approx \sum_{i=1}^{I} \left(\frac{\rho + i + \rho_{fi_{NR}}}{\rho + i + \rho_{fi_R}}\right)^{\frac{b}{a}} \left(1 + b \sum_{i=1}^{I} f_i x_i\right)^{\frac{1}{a}} \tag{18}$$

With the formula in equation (18) it is possible to proxy for the impacts of flood mitigation investments without developing and calibrating a fully-fledged urban economics model and with only a limited set of data. The data needed to inform equation (18) are the construction function parameter b, the real interest rate i, the depreciation rate of structures ρ (commonly assumed to be 0.01), the flood depreciation rates, i.e. the percentage of damages that floods inflict on structures with and without resilience investments which can be retrieved as in this paper through the use of before and after flood maps combined with flood depth - damage curve functions, and finally the distribution of population in urban areas at the grid

cell level, n_i, which can be acquired either with population censuses or through global population data sets such as WorldPop or Landscan[17] for example.

Using this reduced form approximation and using the model's own prediction of the spatial distribution of households in the urban area n_i, we estimate annual and aggregate land value creation from resilience investments to be respectively US$ 8.5 million and US$ 425 million. These numbers are reasonably close to our fully fledged model results of US$ 7.6 million and US$ 379 million but they overestimate them by 12% in both cases. There is always a tradeoff between the benefits and the drawbacks of model complexity. Given the simplicity of producing estimates for the reduced form expression in terms of data and modeling requirements, we consider this to be a promising result and approach that could be used in locations where data is scarce so as to produce quick estimates of land value creation potential from resilience investments.

6   Robustness of the analysis and driving forces

Systematic sensitivity analyses of model results are useful for two reasons. First, whereas most parameter values are the result of a careful calibration procedure, there nonetheless remains irreducible uncertainty, and it is useful to explore the consequences of deviations from the central estimations. Second, aggregate land value creation from resilience investments materializes across a long-time horizon, when housing and land markets have adjusted, new construction has occurred, and households' locational choices have evolved.[18] When we look into the future, even assuming that the static parameters informing the model are perfectly calibrated, there are uncertainties pertaining to their stability over time as various agents' behaviors can vary, for example as a response to exogenous changes in construction techniques.

To evaluate the robustness of the results, we recalculate aggregate land value creation not only using the calibrated model parameters, but also across various combinations of parameterizations. In particular, we recalculate land value creations across 3,000 scenarios in the Closed City with Public ownership of land setting (CCP) and using the conservative flood-depth damage curves provided in Hallegatte et al. (2013). We restrict the sensitivity analysis to one city setting and one flood-depth damage curve because we have already explored the impact of different choices in previous sections and we wish to isolate the contribution of model parameters to land value creation estimates. We choose the CCP setting and the lower bound flood-depth damage curve as these yield more conservative estimates of land value creation from flood mitigation estimates. The choice of the closed city setting is also more likely to be valid in the short to medium-term as potential in-migration cannot happen instantaneously. Each scenario comprises different model parameterization sampled[19] from the uncertainty range as presented in Table 4.[20] It

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[17] Accessible at: https://www.worldpop.org/methods/populations and https://landscan.ornl.gov/.

[18] Local land value increases, as opposed to aggregate net land value change, can occur in the very short term as soon as the flood mitigation works have been announced even, consistent with the assumption of land prices corresponding to their highest and best use and developers/landowners' perfect foresight. We are however interested in aggregate land value creation after land and housing market mediation, which can only manifest itself over time.

[19] We use a Latin Hypercube Sampling (LHS) function and make use of the option to minimize the sum of between-column squared correlations.

[20] Table 4 also presents the values and the signification of the main parameters of the NEDUM-2D model applied to Buenos Aires in our baseline calibration. It also explains how these were obtained (through calibration processes, informed by data, borrowing from the literature or through assumptions), and how these parameter values relate to those found in the literature.

should be noted here that while we explore the impacts of a wide range of parameter values on the model's results, these results should not be interpreted as carrying the same weight. This is because many parameter values (or the combination of parameter values) that we test are highly unlikely and depart both significantly from our calibration values and in most cases from the values found in the literature. The robustness analysis is therefore geared more toward understanding how the model behaves in response to changes in parameter than it is toward understanding how optimistic/pessimistic our central results are.

	Parameter symbol	Parameter value	Uncertainty range	Method of obtention of the central parameter value and other relevant information
Housing production function scale parameter	A	0.25	$0.015 - 40$	Calibrated based on construction costs for various building heights available for 2012 from CLARIN and INDEC.
Elasticity of housing production with respect to capital	b	0.7	$0.4 - 0.95$	Calibrated based on construction costs for various building heights available for 2012 from CLARIN and INDEC. The value of 0.7 calibrated is very close to the value of 0.65 found for France in (Combes, Duranton, and Gobillon 2021).
Share of household income net of transport costs spent on housing	β	0.4	$0.1 - 0.6$	Calibrated. This figure is consistent with official statistics from INDEC which place average expenditure shares at 15.2% and 17.7% respectively for transport and housing and expenditures at 164% of income (INDEC 2013).
Real interest rate: opportunity cost of capital	i	0.02	$0.005 - 0.1$	Assumed as a reasonable value. It is difficult to ascertain a real interest rate that would reflect the annual financial burden of construction in an urban area which has developed over centuries.
Unit cost of time as a fraction of hourly income	t	0.65	_	Calibrated. The value of 0.65 falls within the range of values - [0.5, 1] - reported by most papers (Small and Verhoef 2007; Glaeser, Kahn, and Rappaport 2008).
Depreciation rate of capital	ρ	0.01	_	Assumption that structures on average last for 100 years, which is consistent with (Hallegatte 2009)

Table 4: Main parameters in the NEDUM-2D model applied to Buenos Aires and sensitivity analyses ranges

6.1   How does land value creation change across all sensitivity scenarios?

We first observe the distribution of aggregate land value change across the 3,000 different parameterizations. As shown in Figure 7, aggregate land value change ranges from US$ -6 million to more than US$ 600 million, whereas the annualized land value creation ranges between US$ -0.5 million to more than US$ 15 million. The results found from using the calibrated parameters (US$ 379.04 million for aggregate land value creation and US$ 7.58 million for the annualized one) lie on the right side of the distribution (the 94th percentile of the distribution). Put differently, the outcomes from the calibrated parameters could be categorized as optimistic, as there are only 180 (of 3,000) scenarios for which outcomes are at least as high as these calibrated baseline outcomes. However, when looked across scenarios, the outcomes are quite promising. The average aggregate land value creation across all 3,000 scenarios is US$ 99.22 million, which amounts to almost one-third of the original investment. Further, it

is important to note that the results reported here are based on the CCP setting with lower bound flood damage estimates, which is a conservative model setup, and that many of the sensitivity scenarios are unlikely or very unlikely to materialize as parameters values depart significantly from the calibrated ones.
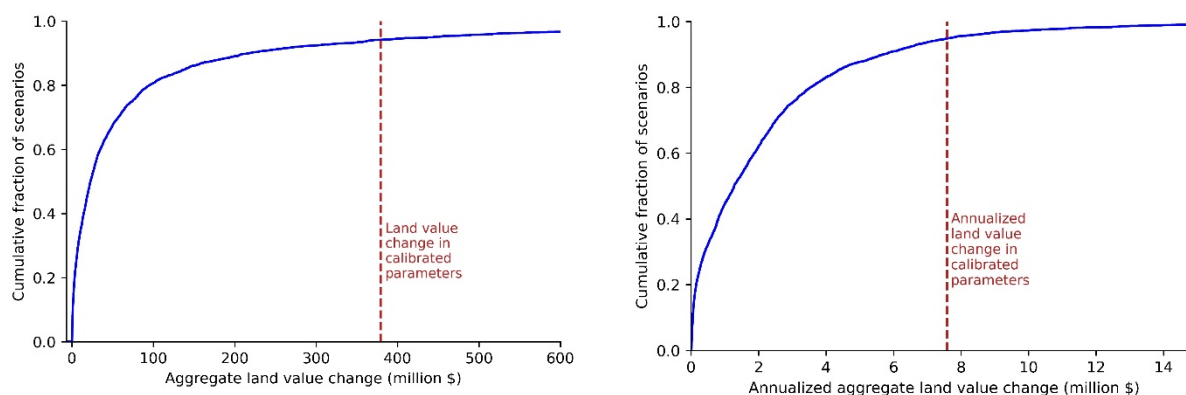

Figure 7: Cumulative distribution of aggregate land value change (left) and annualized land value change (right) across all 3000 scenarios. The outcomes under the calibrated parameter (as presented in Section 4.1 and 4.2) are highlighted as dashed lines.

6.2   Avoiding worst cases: Which scenarios lead to low land value creation?

Figure 7 indicates that in some scenarios land value creation could be fairly low. Here, we identify which particular scenarios result in unfavorable land value creation outcomes. We define unfavorable outcomes as the 20% worst-case scenarios (i.e., aggregate land value creation lower than US$ 3.3 million or 1% of investment cost). As seen in Figure 8, in general, unfavorable outcomes emerge under scenarios with high b parameter (less capital needed for a given amount of housing floor space, hence it is less costly to build taller structures), high A parameter (relatively less capital needed for a given amount of built housing floor space), medium to high real interest rate, and low to medium β parameter (i.e., low to medium share of household income net of transport costs spent on housing). Land value creation is always lower than 1% of the investment cost under scenarios where the real interest rate is very high (>6.8%),[21] the b and A parameters are also very high (0.77-0.95 and 26.67-40, respectively), while the β parameter is not too high (<0.43). This implies that when it is cheap to build housing space, including tall structures, and households are only interested in spending a low share of their income on housing, making structures more resilient to flood damages will only materialize in low land value creation. In other words, having flood-prone land, even centrally located, is not very problematic because it is possible to cheaply build higher elsewhere. This is especially true when the real interest rates are high.

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[21] The real interest rate in Argentina has oscillated between -11% to +11% over the 2010 – 2019 period according to the World Bank's World Development Indicators: https://data.worldbank.org/indicator/FR.INR.RINR?locations=AR.
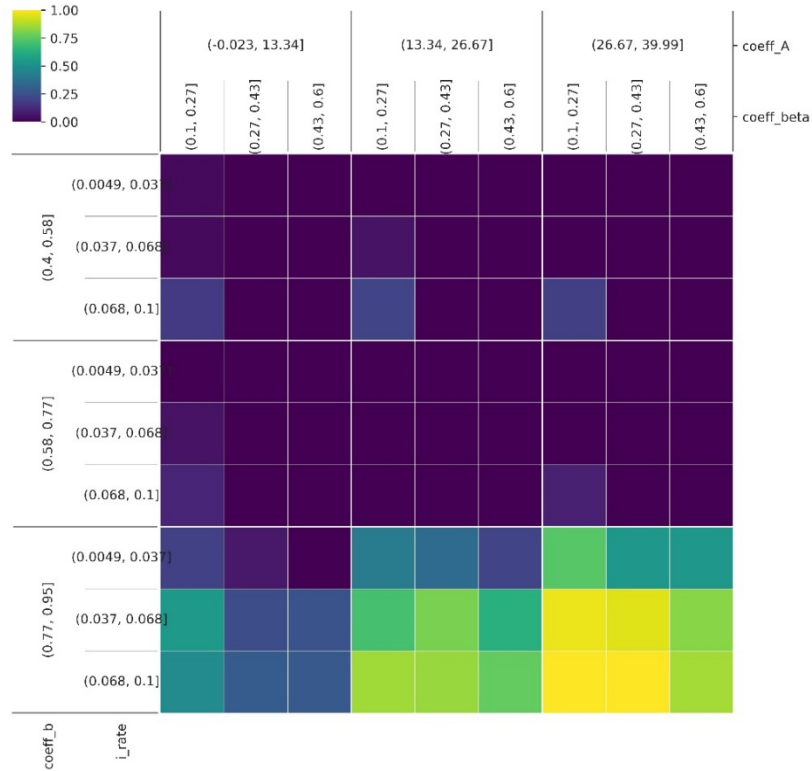
Figure 8 Identification of scenarios leading to low aggregate land value change. The colormap indicates the fraction of scenarios for which land value creation is less than US$ 3.3 million within the given range of parameters. For example, around 75% of scenarios with very high real interest rate, parameter b, parameter β, and parameter A (cell in the bottom right corner) have land value creation of lower than US$ 3.3 million.

6.3   Seizing opportunities: Which scenarios lead to high land value creation?

Instead of looking at worst-case scenarios in terms of land value creation, here we identify conditions leading to favorable outcomes. We define favorable outcomes using two thresholds: scenarios where land value creation is at least one third of the investment cost (Figure 9) or even more than the investment cost itself (Figure 16, in the Appendix). We find that the lower threshold is surpassed in almost 18%, and the upper threshold in almost 7% of the entire scenarios. Figure 9 and Figure 16 (in the appendix) show the scenario identification results for the two thresholds. There are two pathways leading to these favorable outcomes. The similarity between both pathways is that they require the real interest rate to be fairly low (<3.7%) and the β parameter (share of household income net of transport costs spent on housing) to be medium to high. In the first pathway, this is complemented with low to medium b parameter (i.e., more costly to build tall structures) and medium to high A parameter. The second pathway is characterized by medium value of b parameter (between 0.58-0.77, so not too low and not too high) and low to high value of the A parameter. This implies that when it is relatively costly to build tall structures, the annual capital cost of land is relatively cheap and households spend a non-marginal fraction of their budget on housing, land value creation from resilience works is likely to represent a significant share of the initial investment costs. In other words, land is highly valuable when building housing space elsewhere is expensive, so that flood protection works will result in large land value creation.

It is important to note that small deviations from our centrally calibrated parameters, b, A, and β, are unlikely to change whether the land value creation estimates from NEDUM-2D allow to recover at least a third of the initial investment costs. Our central land value creation results are therefore robust to changes in these parameter values. The one parameter in our simplified modeling framework that is hard to ascertain and which leads to very different outcomes in terms of land value creation is the real interest rate, and it has historically been very unstable in Argentina over the last few decades.
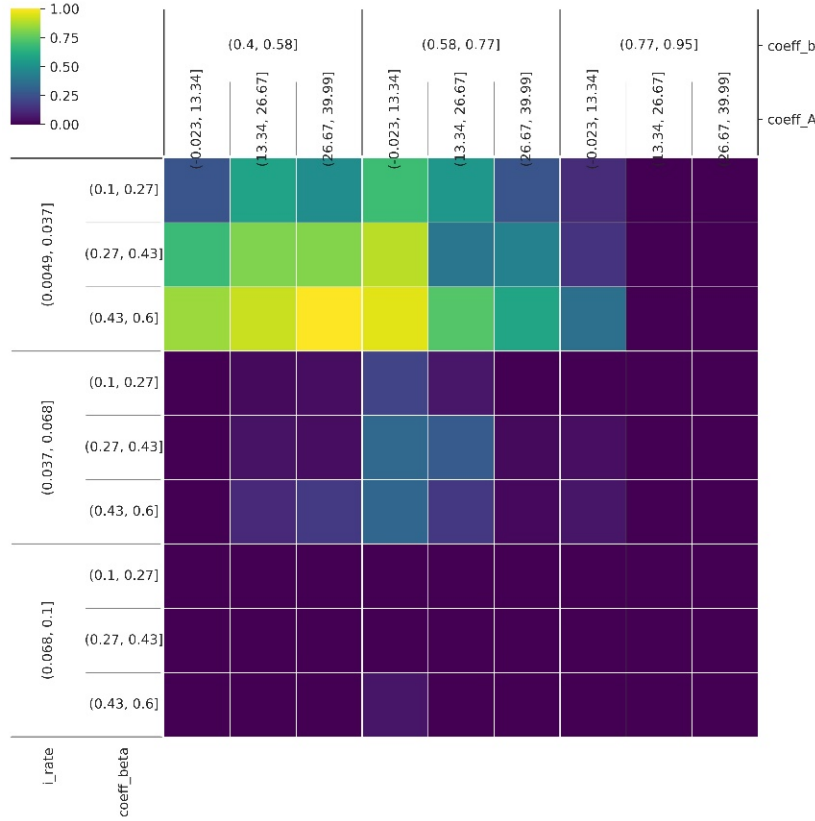

Figure 9: Identification of scenarios leading to favorable outcomes: aggregate land value creation of at least 33% of investment cost.

6.4   What are the driving forces of land value creation and total avoided damages?

Here we try to identify, among the four uncertain parameters, which one has the highest influence on the outcome variables. We use the extra trees algorithm for this purpose (Jaxa-Rozen and Kwakkel 2018), and the results are shown in Figure 10. Overall, we find that the b parameter, which represents the elasticity of housing production with respect to capital, is the most significant driving force across the outcome variables. This translates the fact that land is highly valuable when it is costly to build more elsewhere, that is when land and capital are very imperfect substitutes, i.e. b is low. In these cases, mitigating floods will result in large land value appreciations, all else equal. For annualized land value creation, this is followed by the real interest rate. On the contrary, the most significant driver for aggregate land value creation is the real interest rate, followed by the b parameter. It is important to highlight that the interest rate intervenes in multiple parts of the model, such as in estimating the price of land and thus determining the optimal amount of capital to invest at each location.
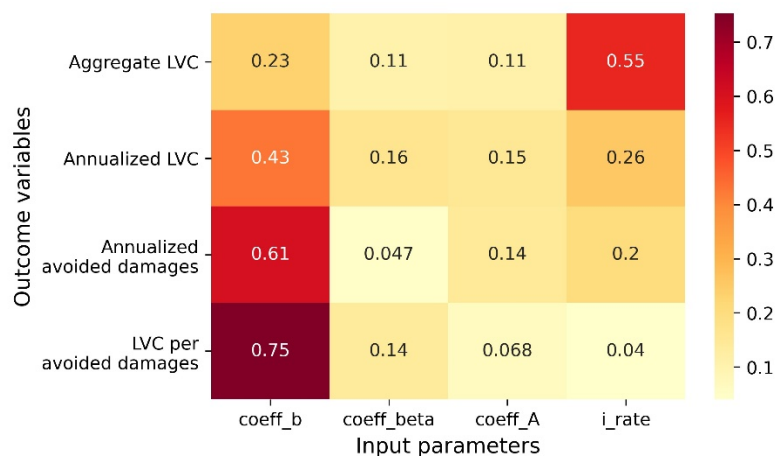
Figure 10 Driving forces of the different outcome variables. The values indicate the total gain in impurity from using the indicated input parameter as the splitting feature in the tree algorithm. Higher values imply higher importance of the input feature in explaining the variance in the outcome variable.

7   Conclusions and discussion

Using a simple urban economics framework, in both a simplified form and calibrated for the urban area of Buenos Aires, this paper shows that the potential for land value creation from resilience investments is real and significant, in particular when flood-prone areas to be protected are valuable because of their proximity to employment centers. Under central, and often conservative, modeling assumptions, land value appreciation alone would justify the upfront investments costs of flood mitigation works. We also show that, in our central setting, net land value creation from resilience is one order of magnitude lower than the value generated from avoided damages to residential structures.[22] However, because appreciated land values as a result of public interventions can appear as more tangible than avoided structural destruction, it might be a more practical and politically acceptable channel through which to implement taxes aiming at recovering part or all of the protection investments costs, and thus more appealing to local decision makers. Another important result from our simulations is that ignoring the land value transfer/destruction linked to land and housing market adjustments would vastly overestimate the aggregate land value appreciation in the urban area (US$ 2.19 billion vs US$ 379 million in our central simulations in a CCP setting). These results tend to support the use of equilibrium models rather than hedonic pricing strategies when the objective is to understand aggregate land value changes from investments rather than purely local ones. If the objective is to estimate local gains only, for example to understand the possibilities of taxing winners, then both methods are useful.

This effort provides several additional insights and contributions. First, whereas relaxing housing regulations in parallel to investing in flood mitigation increases households' utility, it does not translate into higher aggregate land values compared to a scenario in which resilience investments are implemented alone in a closed city setting. This (maybe) surprising result stems from the fact that there are two opposite forces at play: on one hand flood protection in attractive areas leads to higher land values because of lower expected repair costs to buildings and more incentives to build intensively; on the other hand, relaxing housing regulations will reduce housing scarcity and contribute to lowering

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[22] In most scenarios of the sensitivity analysis, this is not the case as most scenarios show land value creation potential to be higher than avoided damages (see Appendix).

housing rents in the urban area and thus land values. Second, while the model presented and used in this paper is, in many aspects, simple, it still requires detailed data sets and implementation time that are likely out of reach for teams in development agencies or cities aiming to produce a quick, yet robust, estimation of land value creation potential from their resilience-focused projects. For this reason, we developed a reduced form version of the model that limits the data needs and can be applied as a first approximation to understand the orders of magnitude of land value appreciation from resilience projects. This reduced form expression provides estimates that were of the same magnitude when tested against the fully calibrated model.

This paper systematically explores the impacts of modeling choices on land value appreciation from resilience investments. It does so, by investigating the impacts of the location of floods on the results of then analysis; by varying the conceptual framework, testing the polar assumptions of open and closed cities and of absentee landlords or public ownership of land; and by using two contrasting flood-depth damage curve functions.

In addition, a detailed sensitivity analysis in the tradition of Robust Decision Making studies is performed to evaluate the impact of parameter values on results. In combination, these analyses highlight which are the most critical parameters and modeling choices when estimating land value creation potential from resilience investments. In terms of the parameters, particular attention should be paid to the elasticity of housing production with respect to capital and the real interest rate influencing people's decision in valuing land prices. The choice of the flood depth – damage curve function also has important implications for the model's results. Finally, the question of whether reduced flood impacts permitted by resilience investments translate into in-migration or not and if so to what extent, captured in our simulations through the election of the closed or open city modeling assumption, is critical to the estimation of land value creation potential: one order of magnitude separates these estimations. Both cases are extreme, albeit useful frameworks, and the appropriate setting probably lies somewhere between the two. The question that remains unanswered, is: is it realistic for local flood mitigation works to trigger in-migration and, if so, to what extent?

Several points deserve discussion at this stage. First, we placed ourselves in a static setting which allows us to look at the long-term impacts of resilience on land value creation potential and to untangle the impacts of these investments from other socio-economic evolutions including demographics. These changes will however only materialize over time as the urban form adjusts to its new risk-profile and building decisions are implemented in reaction. A dynamic version of this model could be used as a next step to investigate the trajectory of land value appreciation. This could be useful for decision makers who are curious about when the initial investments costs could be recovered under various land value taxation schemes.

Second, and more fundamentally, we have assumed a perfect land market, where land prices reflect general attractiveness and flood risk levels, and where construction decisions are only guided by construction costs, including flood depreciation costs, and anticipated housing rents. There are at least two elements that could prevent real-world land markets from behaving as in our applied model: myopic land markets and transaction costs.

With myopic land markets, land values do not fully reflect flood risks as we have posited in our modeling framework, so that construction decisions depart from our simulations. This can happen either because risk information is not widely available or because this information is overlooked by sellers and buyers. In

this case it is likely that protection from floods would also only partially be reflected in land values and construction decisions, reducing the land value creation potential from resilience investments. To what extent land markets account for flood risks is still a relatively open question with most studies finding that flood risks do reduce land and property prices to various degrees (Bin, Kruse, and Landry 2008; Zhang 2016; Zhang and Leonard 2019; Dubé, AbdelHalim, and Devaux 2021; Ortega and Taşpınar 2018). But there at least several papers that either find mixed and weak evidence for property flood risk discount (Beltrán, Maddison, and Elliott 2018; Hino and Burke 2020) or find evidence of land/housing markets adjusting in the aftermath of natural disasters but "forgetting" about the risk several years down the road (Atreya, Ferreira, and Kriesel 2013; Bin and Landry 2013). Ideally our model would be able to account for such myopic land markets. This will be the subject of future work.

A second major bottleneck to the fluid functioning of land markets in developing country cities lies in land right issues and transaction costs involved in converting small scale to larger scale structures (Henderson, Regan, and Venables 2017; Henderson et al. 2016). Land rights issues can arise from multiple claims on specific land plots and the coexistence of private property systems. Such costs can act as a strong disincentive to investing in upgrading structures when and where land becomes more valuable. In our context where resilience investments lead to increased attractiveness of certain locations because of the reduction in background risks, there exists the possibility that such an improvement does not actually translate into increased investments in structures, and land values appreciations remain hypothetical. While we do not have evidence of such land right issues in the central area of Buenos Aires where the flood protection investments are taking place, this topic is nonetheless central for replicating this study elsewhere. Here too, future work will aim and introducing land market frictions in the model.

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9   Appendix

We run a calibration and validation procedure by comparing results (map of urbanized area, real estate/rents, population and housing density) to observed data. Overall, the NEDUM-2D model is very robust as it relies on very simple economic behaviors that are likely to remain true both through space and time. As a consequence, the calibration process is mostly done through refining the data that are used to inform the model. However, a very limited number of parameters can be marginally modified so as to minimize the discrepancies between observations and model results. These include construction cost parameters, household utility function parameters and the cost of time. More detailed description of the data used in this model application to Buenos Aires urban area and the choice of parameter values can be found in Avner et al. (2017).

9.1   Choice of NEDUM-2D model parameters

Table 4 in section 6 presents the values and the signification of the main parameters of the NEDUM-2D model applied to Buenos Aires in our baseline calibration. It also explains how these were obtained (through calibration processes, informed by data, borrowing from the literature or through assumptions), and how these parameter values relate to those found in the literature.

9.2   Data informing NEDUM-2D

9.2.1   Economic and demographic inputs

- Population in the Greater Buenos Aires urban area: Population for the GBA+ region is estimated to be 13,744,044 in 2012 according to projections of the Censo Nacional de Poblacion, Hogares y Vivienda 2001 (CNPHyV 01) for 2012. With an average household size of 3.3, this corresponds to 4,106,479 households.
- Income of the average household: With the version of the model in which we only consider one income class, we need an average income per household. Data from INDEC gives us this information separately for Buenos Aires and the other 'partidos' of the Gran Buenos Aires at trimestral intervals. We thus calculate a weighted average based on their respective household populations for all semesters of year 2012. This yields an average yearly income of AR$ 85,540 or around US$ 18,140.

9.2.2   Transport data and competition between modes

Transport costs are essential to all land use – transport models. NEDUM-2D uses complete or generalized transport costs which encompass both the monetary and time components of travels.

9.2.2.1   Transport times

- Walking times: they are calculated on the basis of the Euclidian distance to the CBD. We assign an average speed of 5km/hour to pedestrians.
- Public transport times: Public transport times were retrieved from the Open Trip Planner Analyst (OTPA) accessibility tool, developed by the World Bank in conjunction with Conveyal. This tool is fed by GTFS data that represents the public transport network and provides Origin-destination travel times at peak and off-peak times. Public transport vehicles in the GBA+ region can be either Colectivo, Ferrocarril, Subte / Premetro, Charter / combi and Bus empresa. These transport times are considered to remain constant throughout the 2012 – 2050 period. This assumption is tantamount to assuming that there will be investments made in currently existing public transport lines in such a manner that the system can absorb population growth without additional congestion. The number of lines and their routes are assumed to remain unchanged throughout the time period.
- Private transport times: Travel times for cars were gathered by collecting Googlemap estimated times systematically throughout the urban area of Buenos Aires. We were able to collect transport times

for trips originating in 9674 different locations (always apart by at least 1km) going far beyond the GBA+ region. As for the public transport infrastructure, it is assumed that there will be investment in roads so that they can absorb a demographic increase without leading to additional congestion. We here again assume that the number of roads will remain constant.

9.2.2.2   Monetary transport costs

- Private car costs: These were estimated to be 0.44 AR$/km or 0.095 US$/km in 2012. They concern both cars and SUVs.
- Public transport fares: The public transport fares were retrieved from the internet for the buses or *Colectivos*. They depend on the distance travelled and we proxied this distance by a bee line distance from origin to destination. The fares do not present a large spatial variation. The ticket costs between US$ 0.65 and US$ 1 in 2012. As a simplification, and because buses are the overwhelmingly used public transport means in the Buenos Aires urban area (87%), it is assumed that the fares for the metro system (*subte*) and trains (*ferrocarril*) are identical to those of the buses.

9.2.2.3   Mode competition and generalized transport costs

Mode competition: The transportation module of the NEDUM-2D model represents modal choice. For each location in the urban area, citizens choose between walking, public transport and private vehicles, or a combination thereof as a means for commuting. The competition between these modes is organized on the basis of their *generalized costs* (i.e. the total cost including both the cost of time and the monetary costs incurred during the trip to the city center). It is assumed in this study that modal switch does not affect congestion levels and therefore leaves commuting times unchanged.

In order to reflect the heterogeneity of citizens' preferences in terms of transport modes we employ a discrete choice model (De Palma and Thisse 1987). We follow a common approach in transportation economics by using a multinomial logit model which assigns usage probabilities to each transport mode (see Salon 2009; Washbrook, Haider, and Jaccard 2006). This method ensures that even when one mode is much cheaper than the others, it will not be used by all residents in a location for all trips. This approach assumes that, for each transport mode i, the inhabitants do not take into consideration the generalized cost p_i, but this cost plus an idiosyncratic random term following a Gumbel distribution. The result is that the probability of choosing mode i in a given location depends on the generalized cost of this mode relative to other modes. The cheaper it is, the higher the probability that it is chosen: the probability to choose the mode i is:

$$P_{m_i} = \frac{e^{-\lambda \frac{p_i}{p_{min}}}}{\sum_k e^{-\lambda \frac{p_k}{p_{min}}}} \tag{A1}$$

where $P_{min} = \min_k(P_k)$ and λ is a coefficient. At a given location, the average transport cost, taking into account all transport modes, is given by the log-sum of generalized transport costs of all modes.

The value of λ is calibrated so as to minimize average mode share discrepancies with the data and is estimated to be equal to 1 in this study. Figure 11 shows the resulting map of one-way generalized commuting costs used in this study.
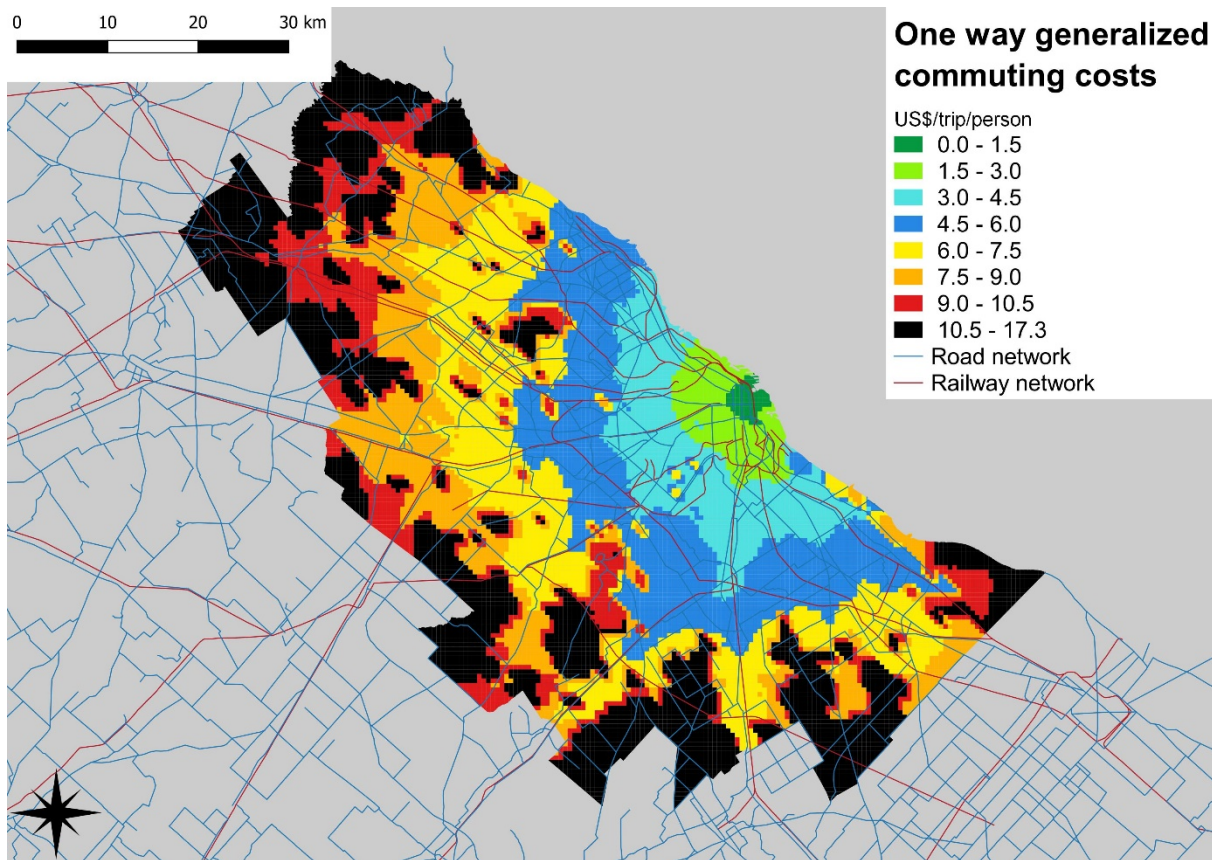
Figure 11: One-way generalized costs of commuting for the GBA+ urban area based on the simplifying hypothesis that all jobs are situated in the center of Buenos Aires. The transport costs thus tend to increase as we move away from downtown Buenos Aires. For a given distance to the center they are lower when one is close to a public transport line.

9.2.3   Land use restrictions

<u>Land uses incompatible with urbanization:</u> In order to be able to reproduce the location and extent of urban areas in the Buenos Aires region correctly, NEDUM-2D accounts for regulations or land uses that are incompatible with the development of residential areas. NEDUM-2D therefore requires a map of land use constraints which is used as a filter to exclude some zones from potential urbanization. For example, it excludes zones occupied by water or protected natural areas such as forests. Water bodies (sea, rivers and lakes) are excluded from potential urbanization as a first step. In a second step a detailed land use map (see Figure 12) is used to identify supplementary zones that need to be excluded from potential urbanization. The exclusion map encompasses any area occupied by protected natural areas, equipment such as the military zones in Campo de Mayo and infrastructure (port, railway station, Ezeiza international airport for example). While the total area of exclusion is non-negligible, it remains, by far, lower than the area that could be potentially urbanized. This is indicative that although the exclusion map can avoid major discrepancies between the simulation and the data, it is not a main driver behind the overall accuracy of our results regarding the match between simulated and observed urbanized areas.
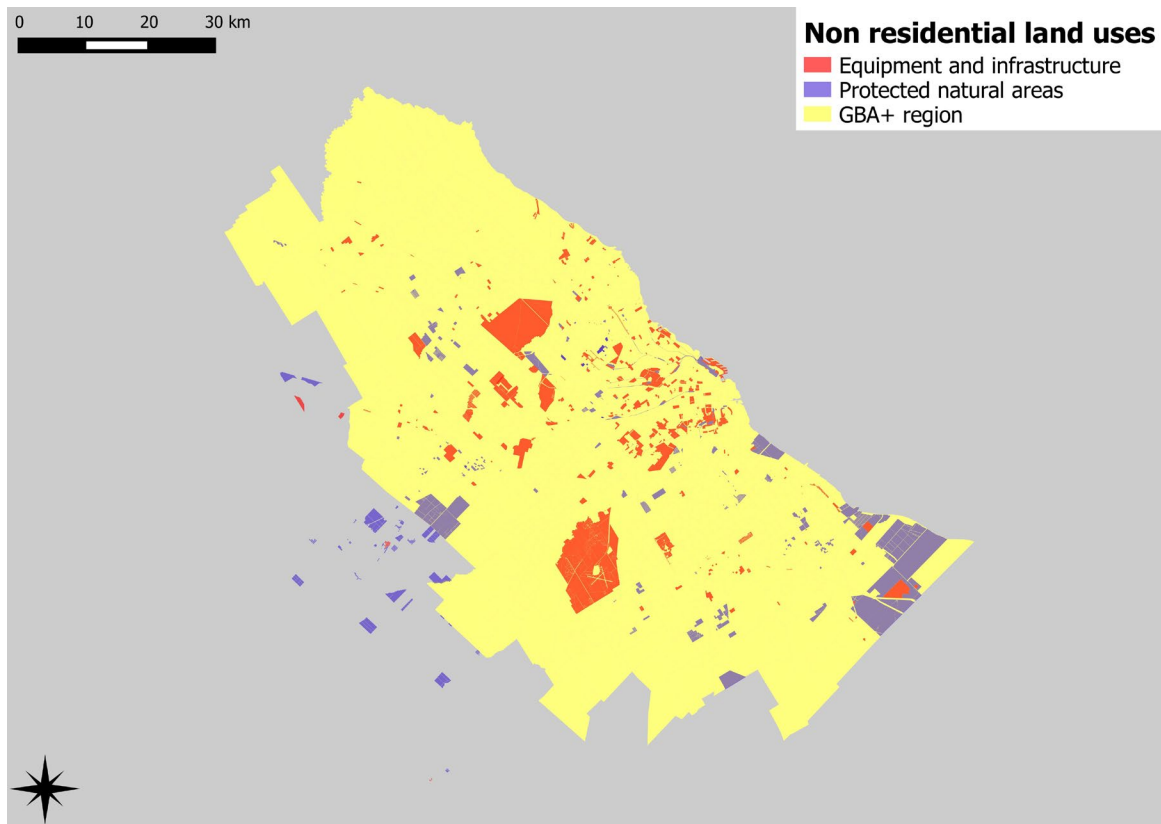
Figure 12: Land use exclusion map showing areas that are excluded from potential urbanization in the model for 2012 (Goytia and Pasquini 2013). Land used for "equipment and infrastructure" or which is labelled as "protected natural areas" cannot be used for residential purposes and is therefore excluded from potential NEDUM-2D simulated urbanization.

<u>Land area available for buildings:</u> We assume that in each pixel of our grid, after excluding for restricted land uses as shown in Figure 12, a maximum of 55% of the land area can be used for buildings. The remaining 45% is expected to be used for roads and infrastructure which are essential for any urban area to function correctly.
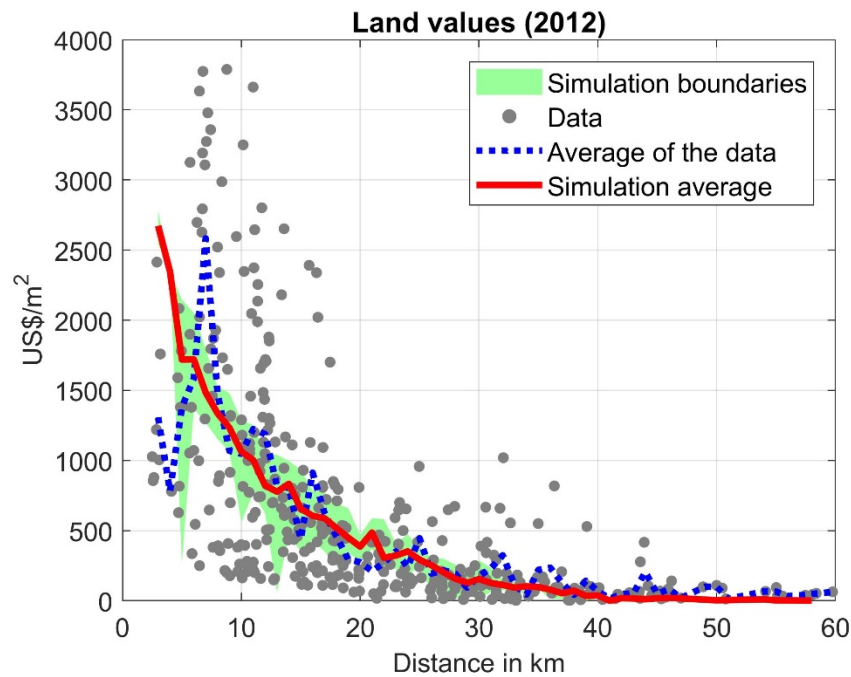
9.3   NEDUM-2D validation

Figure 13 : Simulated and actual land values as a function of the distance to the city center.

Figure 13 shows the classic result that land values decline as the distance to the city center increases both in the data and the simulations. It shows land value data represented by grey circles as well as the average of the data (dashed blue line). The green area captures the spread of the simulations for a given distance to the CBD, while the red plotted line represents the average of the simulation. The one-dimensional R^2 coefficient – comparing the averages of the simulation and the data – is 0.67 meaning that the model can explain 67% of the one-dimensional variance in the data. The two-dimensional R^2 coefficient – comparing each pair of simulation and data points locally – is lower at 32%.
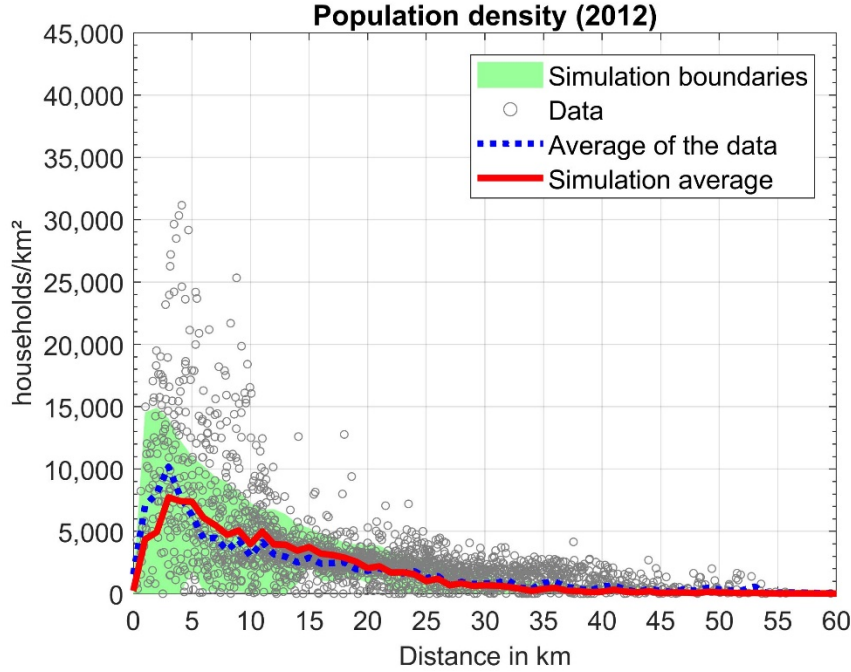
Figure 14 : Simulated and actual population densities for all radios in GBA+ as a function of the distance to the city center.

Figure 14 has the same color codes and purpose as Figure 13 but looks into whether and to what extent the simulations and the data agree for population densities (households/km²) at the *zonificaciòn* administrative level, which is slightly larger than a census tract. A similar conclusion can be drawn from the figure, that there is a generally good agreement on the shape of the two curves representing the averages of the data and the simulations. In particular, toward the city center, both curves display similar spikes and slumps. The model's spread also captures a large share of the data points (grey circles), although there is a greater dispersion in population densities of radios (census tracts) within 10km of the CBD that the model only partially accounts for. The one-dimensional R^2 coefficient is high at 0.87 meaning that the model can explain 87% of the variance between the simulation and data average. The two-dimensional R^2 coefficient comparing data and simulation at the census tract level, and accounting for the population of each census tract, is lower at 0.53.

Finally, the model is also validated against several figures that describe mobility behaviors for households in the Buenos Aires metropolitan area. The mode share for public transportation, which is determined endogenously in NEDUM-2D, is 55.5%, very close to the 57% average figure reported by the ENMODO mobility survey for the AMBA region (Ministerio del Interior y Transporte 2010). The average commuting times computed by the model is 57 minutes so slightly higher than, yet in the same magnitude order as the 44 to 49 minutes reported by ENMODO.

9.4   Land value creation approximation: utility changes from resilience investments

One main difficulty from the expression found in equation (16) is how to value the $\left(\frac{R_{0_R}}{R_{0_{NR}}}\right)$ term without relying on a fully fledged urban model, in other words: how can we proxy for the change in household utility? We provide here a rapid estimation method.

Let N be the total city population. We have:

$$dN = \int \frac{dH}{dq} - \int \frac{H}{q}\frac{dq}{q}$$

$$dN = \int \frac{1}{q}\left(\frac{bH}{aR_0}dR_0 - \frac{bH}{a(\rho + i + \rho_f)}d\rho_f\right) + \int \frac{H}{qR_0}dR_0$$

$$dN = \int \frac{1}{aq}\left(H\frac{dR_0}{R_0} - bH\frac{d\rho_f}{(\rho + i + \rho_f)}\right)$$

$$dN = \frac{N}{a}\int \frac{dR_0}{R_0} - \frac{b}{a}\int n\frac{d\rho_f}{(\rho + i + \rho_f)}$$

where n is population density. In a close city model we have dN=0, so:

$$\int \frac{dR_0}{R_0} = b\int \frac{n}{N}\frac{d\rho_f}{(\rho + i + \rho_f)} \tag{19}$$

Equation (19) means that, if for a fraction f of the total city population, floods damages variation reaches $x\%$ of total buildings ownership costs, then $\frac{R_{0_R}}{R_{0_{NR}}}$ will be approximately $1 + bfx$. If, in one part of the city, for a fraction f_1 of the population, floods damages variation reaches $x_1\%$ of total buildings ownership costs, and in another part $x_2\%$ for a fraction f_2, then we will have:

$$\frac{R_{0_R}}{R_{0_{NR}}} \approx 1 + bf_1x_1 + bf_2x_2 + \cdots$$

9.5 Supplementary sensitivity results

9.5.1 *Beyond land value creation: Impacts of parameters on avoided damages*

The parametric uncertainties embedded in the scenarios influence not only land value creation, but also avoided direct damages. In the calibrated parameters, the annualized land value creation amounts to around 16% of the annualized avoided direct damages (see Section 4.2). Figure 15 shows that the baseline result rests on the left side of the distribution (around the 15th percentile). In more than 2,550 scenarios, the ratio between annualized land value creation and avoided damages is higher than 16%, and this could even go as high as 250% (i.e., land value creation is 2.5 times higher than avoided direct damages). In half of the entire 3,000 scenarios, the ratio is higher than 80%. These findings indicate robust results that indirect benefits from land value creation cover a considerable portion of, or even higher than, the expected annualized direct damages. This provides an even stronger impetus to account for such indirect benefits when planning for resilience investments.
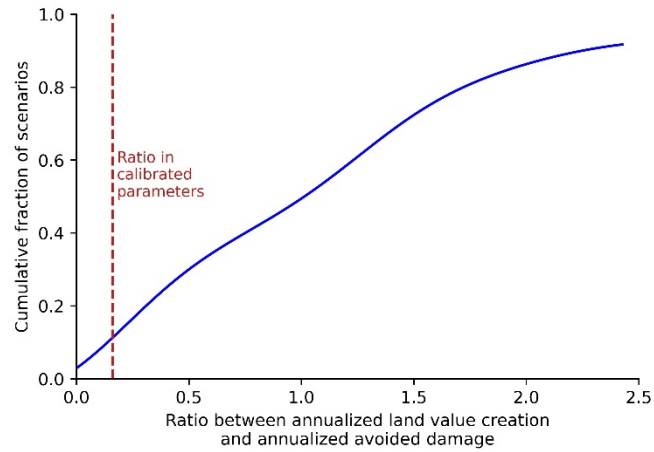
Figure 15 Cumulative distribution of ratio between annualized land value creation and annualized avoided damages across all 3000 scenarios.

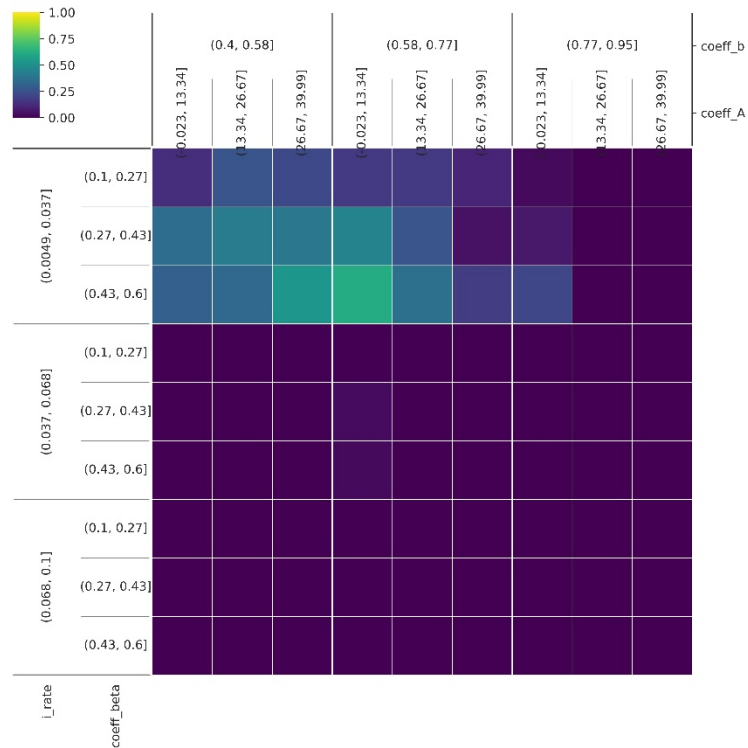## 9.5.2   Parameters leading to investment costs recouping

Figure 16 Identification of scenarios leading to favorable outcomes: aggregate land value creation of at least 100% of investment cost.