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The affordability of property-level adaptation measures against flooding is crucial due to the movement toward integrated flood risk management, which requires the individuals threatened by flooding to actively manage flooding. It is surprising to find that affordability is not often discussed, given the important roles that affordability and social justice play regarding flood risk management. This article provides a starting point for investigating the potential rate of unaffordability of flood risk property-level adaptation measures across Europe using two definitions of affordability, which are combined with two different affordability thresholds from within flood risk research. It uses concepts of investment and payment affordability, with affordability thresholds based on residual income and expenditure definitions of unaffordability. These concepts, in turn, are linked with social justice through fairness concerns, in that, all should have equal capability to act, of which affordability is one avenue. In doing so, it was found that, for a large proportion of Europe, property owners generally cannot afford to make one-time payment of the cost of protective measures. These can be made affordable with installment payment mechanisms or similar mechanisms that spread costs over time. Therefore, the movement toward greater obligations for flood-prone residents to actively adapt to flooding should be accompanied by socially accessible financing mechanisms.

KEY WORDS: Affordability; flood risk; social justice; risk reduction

1. INTRODUCTION

Flooding is a significant threat to humanity (UNISDR, 2011), which leads to investments in protective measures. Structural measures, such as dikes, are a common investment as these measures aim to prevent flooding. However, structural measures are expensive, and as such investment decisions balance protective capability with cost. Thus, it is unlikely that structural measures will protect against all possible floods as costs grow compared to the expected benefit (Merz, Kreibich, & Apel, 2008).

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This outcome has resulted in a movement toward integrated flood risk management, which requires all individuals threatened by flooding to limit flood risk in accordance with their capabilities (Bubeck, Aerts, de Moel, & Kreibich, 2016) as a complement to more traditional approaches. For example, flood-prone property owners in Germany are required to undertake measures that limit flood damage wherever possible (Thieken et al., 2016b). Therefore, there has been much research into the employment and cost-effectiveness of property-level adaptation (de Ruig, Haer, de Moel, Botzen, & Aerts, 2019; DEFRA, 2008; Hudson, Botzen, Kreibich, Bubeck, & Aerts, 2014; Kreibich, Christenberger, & Schwarze, 2011; Lamond, Rose, Bhattacharya-Mis, & Joseph, 2018; Poussin, Botzen, & Aerts, 2015) within this environment of changing responsibilities (see

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Bogliacino, Codagnone, & Veltri (2016), for a discussion across policy areas).

Property-level adaptation measures are broadly split into dry flood-proofing, which prevents floodwater from entering a building, and wet flood-proofing, which limits flood damage once water has entered a building. Kreibich, Bubeck, Van Vliet, and De Moel (2015) reviewed the literature on the effectiveness of property-level measures, indicating that property-level measures can be cost beneficial and can play a useful, and complementary, role in flood risk management. This finding has led to these measures being linked with insurance (Michel-Kerjan, 2010; Michel-Kerjan & Kunreuther, 2011; Surminski, 2014). This is because insurance is often assumed to incentivize additional risk reduction by policyholders. However, an active link between insurance and property-level adaptation is not strongly present across Europe (Surminski et al., 2015) or many other jurisdictions across the world (Kunreuther, 1996; Thistlethwaite, Henstra, Brown, & Scott, 2018). Despite this, the affordability of insurance premiums is a concern as, while risk-reflective premiums potentially provide the strongest incentives, they can also become unaffordable. For instance, Kousky and Kunreuther (2014) find an unaffordability rate of 35% for Ocean County, New Jersey. FEMA (2018) find that low- and medium-income households are forgoing insurance as it is seen to be unaffordable. Hudson, Botzen, Feyen, and Aerts (2016) find that about 20% of households at risk of flooding in France and Germany find risk-based premiums unaffordable, when judged in relation to the level of a household's income relative to a poverty line.

The ability to afford property-level adaptation measures is linked to broader socioeconomic inequalities (Kaufmann, Priest, & Leroy, 2018) and the fairness of flood risk management approaches (Thaler, Fuchs, Priest, & Doorn, 2018) through its social justice implications. This is because once an adaptation strategy is unaffordable, those exposed to flooding face additional unfair burdens in managing flood impacts. The redistribution of responsibilities under integrated flood risk management could lead to new patterns of inequality and injustice. Therefore, potentially unequal distribution of burden is an important concern in an environment of increase mandates to act.

While there is not a single concept of justice, the concept of justice employed in the current study draws upon the fairness principles of Johnson, Penning-Rowsell, and Parker (2007). Therefore, based on this concept of justice, all of those threatened should have an equal opportunity and capacity to adapt, which is important when new obligations are introduced. Those who are significantly financially burdened may require additional assistance (Johnson et al., 2007; Montgomery & Kunreuther, 2018; Sayers, Penning-Rowsell, & Horritt, 2018).

This article provides a starting point for empirically operationalizing an aspect of social justice in flood risk adaptation based and developed upon the fairness principles of Johnson et al. (2007). This is done by investigating what can be considered a fair or affordable contribution toward property-level flood risk adaptation measures across the European Union (EU). The potential rate of unaffordability of property-level flood risk adaptation measures is measured using two definitions of affordability, which are combined with two different affordability thresholds from within flood risk research. The EU scale of this article is relevant in terms of Floods Directive, and similar, which requires that while countries can approach flood risk management in their own way, there is an implict degree, or intention, of degree of comparability between published risk management plans or outcomes for countries to compare and learn from each other. Therefore, this study acts within this environment by employing a common methodology and public data source to provide an initial indication of the state of affordability.

The concept of affordability helps in understanding the justice implications of integrated flood risk management decision making (Thaler et al., 2018) by acting as a metric concerning fair flood risk management. This is in addition to wider indicators of social vulnerability, see, for example, Cutter, Boruff, and Shirley (2003), which include factors such as employment status, education level, age, local infrastructure quality, that can operate at both the regional and individual levels as the concept of affordability does but are less focused as a fairness metric. While it is uncertain whether or not flood-prone areas contain a substantial number of socially vulnerable individuals (Collins, Grineski, & Chakraborty, 2018; Cutter, Ash, & Emrich, 2014; Hale, Flint, Jackson-Smith, & Endter-Wada, 2018; Koks, Jongman, Husby, & Botzen, 2015), the socially vulnerable are more heavily subjectively impacted by flooding (Bubeck & Thieken, 2018; Cutter, 2017; Hale et al., 2018; Hudson, Pham, & Bubeck, 2019). They also can have more limited abilities to absorb or to recover from flood events, leading to larger subjective impacts (Kaufmann et al., 2018; Walker & Burningham, 2011). This disproportionate effect is the result of unequal levels of community and individual resilience (Kaufmann et al., 2018), which is measured across their ability to resist (to lower impacts), recover (to bounce back), or possess adaptive capacity (the ability to learn and improve; Thieken, Mariani, Longfield, & Vanneuville, 2014). Addressing affordability offers an avenue for addressing this resilience gap by taking into account the ability of individuals to contribute a "fair" amount of resources toward flood risk management (an aspect of adaptive capacity).

The results suggest the need for mechanisms for helping the lower income residents of flood-prone areas to adapt to flooding. Low-cost loans are an often suggested way of doing so (e.g., Botzen & van den Bergh, 2008, or Montgomery & Kunreuther, 2018). When such mechanisms are employed, the large difference between rates of unaffordability implies the importance of considering how households finance this investment. Many current studies considering property-level adaptation, in effect, assume that households have access to suitable financing mechanisms and can employ them if the measure is found to be cost-beneficial. This assumption may not hold and therefore could be one factor inhibiting the development of property-level risk management. While these affordability-enhancing measures have been suggested in the wider literature, this is the first article that directly measures and highlights their importance. This is relevant with the increasing focus on action by residents in flood-prone areas, whereby an increasing focus should be placed on social justice considerations.

2. DATA AND METHODS

The methodology and data are discussed below, and summarized in Fig. 1.

2.1. Property-Level Flood Adaptation Measures

2.1.1. Effectiveness

Considering the effectiveness of property-level adaptation is a first step in studying affordability. Measures that are not cost-beneficial are not a useful expenditure and as such are a negative burden if employed.

In the wider scientific literature, Kreibich et al. (2015) find a mean effectiveness estimate for dry flood-proofing of 45% of damage prevented (range = 10%–85%) and 35% (range = 10%–53%) for wet flood-proofing. However, these estimates may represent the upper boundary of effectiveness due to the influence of local conditions (Hudson et al., 2014; Kreibich et al., 2015; Poussin et al., 2015); the complexities of studying fragmentary, heterogeneous, and incomplete impact data (Schröter, Molinari, Kunz, & Kreibich, 2018; Thieken et al., 2016a); and different modeling/empirical identification strategies (Kreibich et al., 2015). However, property-level adaptation measures are overall cost-beneficial when there is a 2%–5% flooding probability (DEFRA, 2008; Hudson et al., 2014; Kreibich et al., 2011; Lamond et al., 2018; Poussin et al., 2015), and smaller/cheaper investments such as oil tank protection are invested in (Kreibich et al., 2015).

However, dry flood-proofing is more appropriate in minor flood potential areas as such measures can be overtopped (Kreibich, Thieken, Petrow, Müller, & Merz, 2005) or face physical limitations due to hydrostatic pressures after ~1 m (Aerts, 2018). Wet flood-proofing does not face this issue and may be better suited to areas with greater flood potential. Additionally, May and Chatterton (2012) have highlighted that property-level adaptation measures could be associated with a reliability of 77%–90%, with measures that do not need to be redeployed displaying higher reliability.

Overall, despite these limitations, property-level adaptation can play a role in managing flooding, as a complement to structural measures based on the findings within wider literature.

2.1.2. Costs

Detailed information on costs per building is limited (Kreibich et al., 2015) and uncertain (Aerts, 2018) as the cost of building-level adaptation is highly variable. Individual building costs depend on a range of factors such as the type, age, and size of a property and the expected type, depth, and duration of flooding. A common simplification is to average across building classes (Lamond et al., 2018), including, in effect, the current study.

A systematic literature review of dry and wet flood-proofing costs is presented in Aerts (2018), who focuses on two cost types: construction costs and

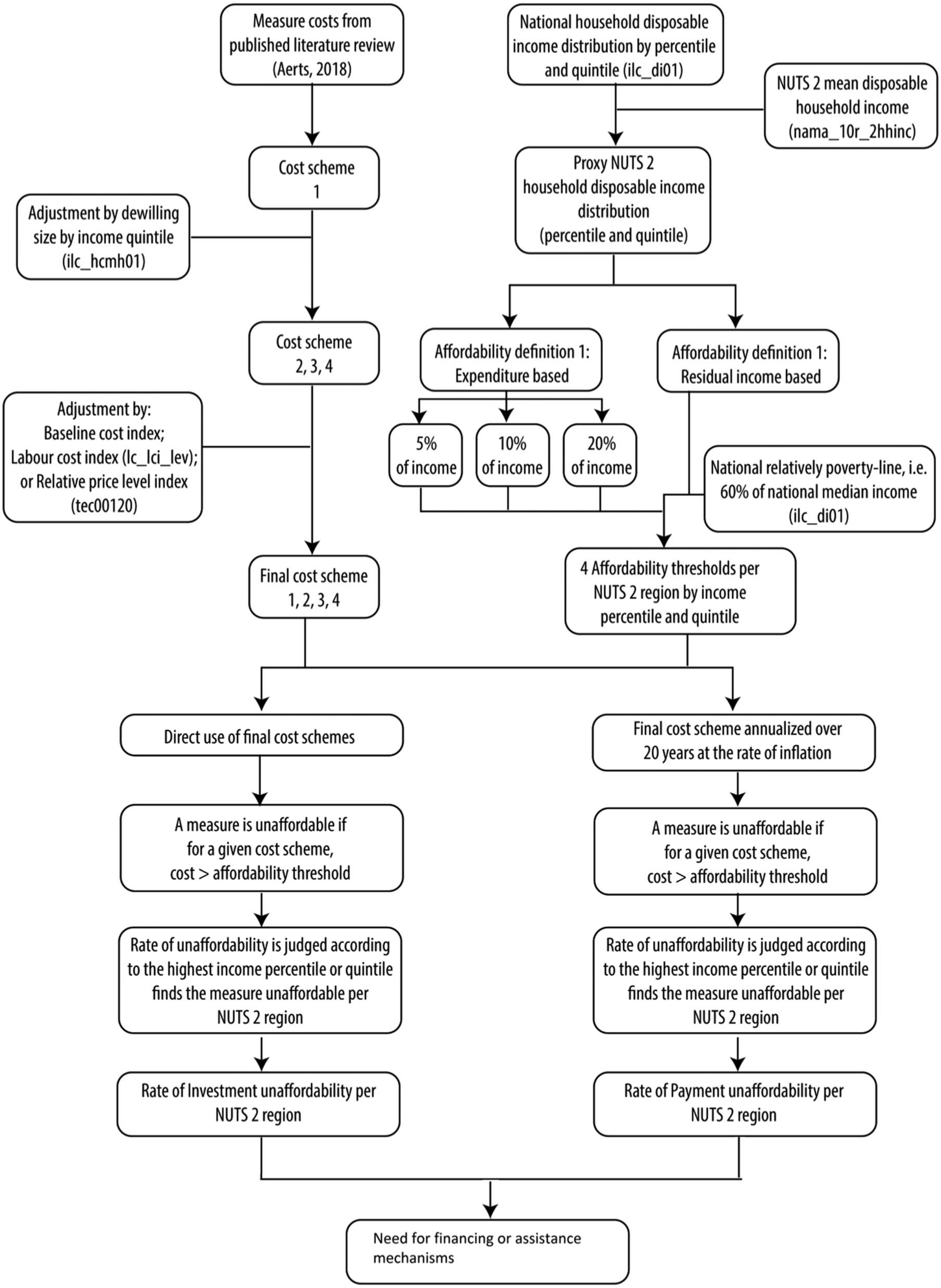

Fig. 1. Flowchart of the study's methodological process.

operation and maintenance costs. Aerts defines construction costs as fixed, one-time expenses such as planning, purchasing materials and machinery, land acquisition, construction labor, permits. While operation and maintenance costs include yearly costs needed to operate, maintain, monitor, and replace equipment, Aerts finds that in many cases specific cost estimates were either not provided or cost information was incomplete. Aerts notes that these costs are distributed over developed and developing countries.

In order to use suitable costs from Aerts (2018), due to the current study's focus on Europe, the estimates from the United Kingdom and Germany are most relevant (followed by the United States). This provides a baseline estimate from Western Europe. Aerts finds that, in terms of construction costs, in the United Kingdom, dry flood-proofing residential buildings, for ~1 m of dry proofing, costs $13,000–$18,200 (2008 dollars). Aerts finds an estimate of $732 (2011 dollars) per meter of dry flood-proofing in Germany. For wet flood-proofing, the U.K. estimate is $8,073–$18,369 (2008 dollars) for a residential building and a total cost of $22,237 (2011 dollars) for a 65 m^2 residential building in Germany. Concerning maintenance costs, maintenance costs per year are estimated at 1%–3% of the construction costs for dry flood-proofing, and at less than 1% of investment costs. Therefore, maintenance costs are included for dry flood-proofing but not wet flood-proofing. These values, in 2015 euros, are presented as Scheme 1 in Table I.

These estimates provide a cost baseline to be further altered according to dwelling size. As an illustration, the average dwelling size for those in the bottom 20% of income across the EU is 81 m^2, while for the top 20% the average dwelling size is 114 m^2 (Eurostat variable ID: *ilc_hcmh01*). In order to differentiate costs by dwelling size, three approaches are used. The first is a rescaling of Scheme 1 by the ratio of the mean dwelling size within an income quintile relative to the European average (Eurostat variable ID: *ilc_hcmh01*). Therefore, a dwelling that is 20% larger than the European average dwelling has 20% larger costs. See Scheme 2 in Table I.

The second approach uses the dwelling sizes in Germany and the United Kingdom and costs in Scheme 1 to produce costs per linear meter of dry flood-proofing and per square meter for wet flood-proofing. This approach was used in Aerts, Botzen, and de Moel (2013) for New York City. This results in a cost range of €423 to €695 per linear meter of dry flood-proofing (based on the building's perimeter) in 2015 euros once maintenance costs are included. The corresponding value for wet flood-proofing is €104–€332 per m^2. When costs per building are estimated, the costs for dry flood-proofing are €16,000–€27,000 and €9,400–€30,000 for wet flood-proofing. See Scheme 3 in Table I.

The final cost scheme, Scheme 4, also uses the above approach but is combined with the U.S. cost data presented in Aerts et al. (2013). While the costs for retrofitting buildings in the United States and Europe may differ, the approach has been successfully employed, such as in Austria (Unterberger, Hudson, Botzen, Schroeer, & Steininger, 2019). The costs following Scheme 4, in 2015 euros, result in an average cost of €10,800 for dry flood-proofing and €2,700 for wet flood-proofing.

Moreover, as was noted, cost-effective property-level adaptation measures tend to be smaller/cheaper measures (Kreibich et al., 2015), which are associated with the lower cost estimate. Therefore, the lower cost estimate is focused upon to represent the most optimistic case. Bureaucratic cost categories, for example, permits or building surveys, are excluded from this analysis as a simplification. A further caveat is that these estimates may be rather generic and use older (potentially outdated) sources.

2.2. Affordability

2.2.1. Affordability Definitions

There is no single definition of affordability due to its normative nature (National Research Council, 2015; Saenz, 2009). However, it is considered that a purchase is affordable if it does not result in the purchaser facing a financial burden at the time of purchase (National Research Council, 2015). In essence, this can be seen as a fair contribution of resources toward adaptation, which naturally overlaps with the social justice fairness and their adaptive capacity to act. The focus of affordability is on budgets rather than potential benefits. A measure can bring long-run benefits and be an immediate burden, limiting adaptive capacity.

A complication regarding the affordability of property-level adaptation measures, as compared to flood insurance, is that property-level adaptation measures are stock variables. Therefore, additional formulation is required. The first is "investment affordability," which is the ability to buy or to access sufficient resources that allow for a purchase.

Table I. Costs of Wet and Dry Flood-Proofing Following Aerts et al. (2013) and Aerts (2018)

	Flood-Proofing Adaptation Costs				
	(**Scheme 1**) Average Cost per Building	(**Scheme 2**) Adjusted Average Costs per Building	(**Scheme 3**) Cost per Square/Linear Meter on European Costs (~1 m)	(**Scheme 4**) Cost per Square/Linear Meter on American Costs (~1 m)	Size of Dwelling (across the European Union and Income Groups)
Wet flood-proofing	€2,100–€20,600	€1,700–€23,000	€104–€332 per m^2	€33 per m^2	96 m^2
Dry flood-proofing	€7,900–€20,200	€6,300–€23,000	€423 and €695 per linear meter	€285 per linear meter	39 m perimeter

The second is "payment affordability," which is concerned with the series of annualized expenditures on the measure. Investment affordability is applicable when there is less ability to intertemporally spread the resources needed to by an adaptation measure. Payment affordability is the reverse.

The comparison of outcomes under both affordability definitions indicates the importance of having such cost-spreading mechanism. The literature regarding property-level adaptation does not actively consider the resources available to the potential employer or tend to focus on other elements of the decision-making process. The larger the magnitude of the difference between the two concepts of affordability, there is a greater need to consider the fairness aspects of adaptation, of which affordability is one element. One expectation is Montgomery and Kunreuther (2018) who conduct a cost–benefit analysis of elevating households in a region of the United States, both for a single up-front payment and when loans are provided. While Montgomery and Kunreuther did not focus on investigating affordability, their study highlights the relevance of affordability.

2.2.2. *Affordability Thresholds*

In this analysis, two threshold categories are assumed across investment and payment affordability. The first threshold assumes that a property-level adaptation measure is affordable if the expenditure lies below a certain percentage of disposable income. For example, Kousky and Kunreuther (2014) use a 5% of income threshold for calculating flood insurance affordability. The expenditure definition is shown in Equation (1), where a property-level adaptation measure is affordable under the expenditure threshold ($A^{ET}_{i,j,c}$) for individual *i* if the expenditure on a given property-level adaptation measure ($E^M_{i,j}$) is below a certain percentage (α) of disposable income ($I^d_{i,j,c}$). An expenditure threshold of 5% of disposable income is selected, matching Kousky and Kunreuther (2014), with complementary values of 10% and 20%. A value of A^{ET}_i equal to 1 indicates that the measure is affordable and 0 if not.

$$A^{ET}_i = \begin{cases} 1 \text{ if } E^M_i \leq \alpha I^d_i \\ 0 \text{ if } E^M_i > \alpha I^d_i \end{cases}. \quad (1)$$

The second definition is focused on poverty-line indicators, as in Hudson et al. (2016). This approach indicates that a property-level adaptation measure is affordable if the buyer is left with a minimum disposable, or residual, income after the purchase (Equation (2)). For residual income threshold (A^{RIT}_i), a measure is affordable if a purchase does not lower the purchaser's remaining disposable income to below the relative poverty line in a given country (PL_c), which is 60% of the national median disposable income (a preexisting definition across Europe).

$$A^{RIT}_i = \begin{cases} 1 \text{ if } E^M_i \leq I^d_i - PL_c \\ 0 \text{ if } E^M_i > I^d_i - PL_c \end{cases}. \quad (2)$$

However, in practice, threshold values should be selected by local stakeholders (National Research Council, 2015) but using a single definition across regions generates a basis for comparison.

2.2.3. *Payment Structures*

Investment affordability directly compares the price of a given measure with income, as the purchase is a single upfront payment. Payment affordability applies when a series of annualized payment is made for a given measure. One suggested mechanism to annualize payments is low-cost loans, as in Botzen and van den Bergh (2008) or Montgomery and Kunreuther (2018). Additionally, in assuming the presence of low-cost loans investment affordability is no longer relevant, as the loan provides sufficient resources instead. Therefore, the ability to annualize costs changes the relevant concept of affordability in a similar way to mortgages and property purchases.

The annual repayments (M) are, following Equation (3), related to a fixed interest rate r and the number of years (n) for the loan's repayment period. However, as the loans purpose is to spread the financial cost of a measure, it is possible that other mechanisms can achieve the same outcome (see Section 3.4).

$$P_i^M = E_i^M \frac{r(1+r)^n}{(1+r)^n - 1}. \tag{3}$$

Across the Eurozone, mortgages tend to be issued with a maturity ranging between 20 and 30 years (ECB, 2009), which matches the expected life span of dry and wet flood-proofing (Aerts, 2018). The rate of inflation is selected as the interest rate to maintain the loan's real value. This is due to the mechanism aiming to maximize social access to adaptation measures. It is possible that in practice higher interest rates will be charged in order to cover the possibility of defaults.

2.2.4. Household Income

In order to investigate affordability, data on income distribution are required, which are not available from a single source. Therefore, household income data are based on an approximation of the Nomenclature of Territorial Units for Statistics (NUTS) two-level household-level disposable income, which was the lowest spatial data level available for a study operating at a high level across Europe.

The first step was to collect data from the European Union Statistics on Income and Living Conditions (EU-SILC) database for 2015 (variable ID: *ilc_di01*) on disposable income, as the latest year with the most complete information. Data were extracted for the top cutoff points for the 1st, 2nd, 3rd, 4th, 5th, 10th, 20th, 25th, 30th, 40th, 50th, 60th, 70th, 75th, 80th, 90th, 95th, 96th, 97th, 98th, and 99th percentiles. Missing values were interpolated as a linear increase between known values.

However, EU-SILC data are at the national level and, as such, are complemented by regional data for mean disposable household income (Eurostat variable ID: *nama_10r_2hhinc*). In order to generate regional income distributions, the national income distribution was downscaled. This was done by dividing each income percentile for a specific country by that country's mean income. This provided a scaling ratio for each income percentile relative to the mean income, and the mean disposable income per region was then rescaled. This produces country-specific income distribution shapes (e.g., France and Germany have different distributions), which centered on different values for a given region (i.e., each NUTS 2 region within a country is positioned differently). This assumption abstracts away how income distributions differ in flood-prone areas, the patterns of which may also differ across different flood types (Walker & Burningham, 2011), or between more rural and urban areas.

3. RESULTS AND DISCUSSION

3.1. Rates of Investment Unaffordability

3.1.1. Residual Income Threshold

The levels of investment unaffordability across regions are presented in Fig. 2 based on the residual income definition for the average quintile for which dry or wet flood-proofing is found to be unaffordable across the cost schemes. For dry flood-proofing (Panel A), the highest model quintile at which dry flood-proofing becomes unaffordable is the third income quintile for Cost Schemes 1, 2, and 4, which increases to the fourth quintile under Cost Scheme 3. The spatial pattern for the average highest quintile of unaffordability is also indicated in Fig. 2, averaged across cost schemes. The highest rates of unaffordability are found in Eastern Europe, the Baltic States, southern Iberia, and southern Belgium, as the rates of unaffordability in these locations lie between the 3.75th and 5th income quintiles. Austria, Southern Germany, the United Kingdom, and Ireland have the lowest rates of unaffordability for dry flood-proofing, lying between the 1.75th and 3rd income quintiles.

Turning to wet flood-proofing (Panel B), under the residual income distribution, the highest model quintile at which dry flood-proofing becomes unaffordable is the first quintile for Cost Schemes 1, 2, and 4, which increases to the third quintile under Cost Scheme 3. Overall, the rates of unaffordability are lower for wet flood-proofing (as seen in Fig. 2). Northern Europe, Western Europe, and Northern Italy display rates of unaffordability for wet flood-proofing below the second income quintile. Southern Europe and the Baltic States tend to be located between the 2nd and 2.75th income quintiles. Eastern

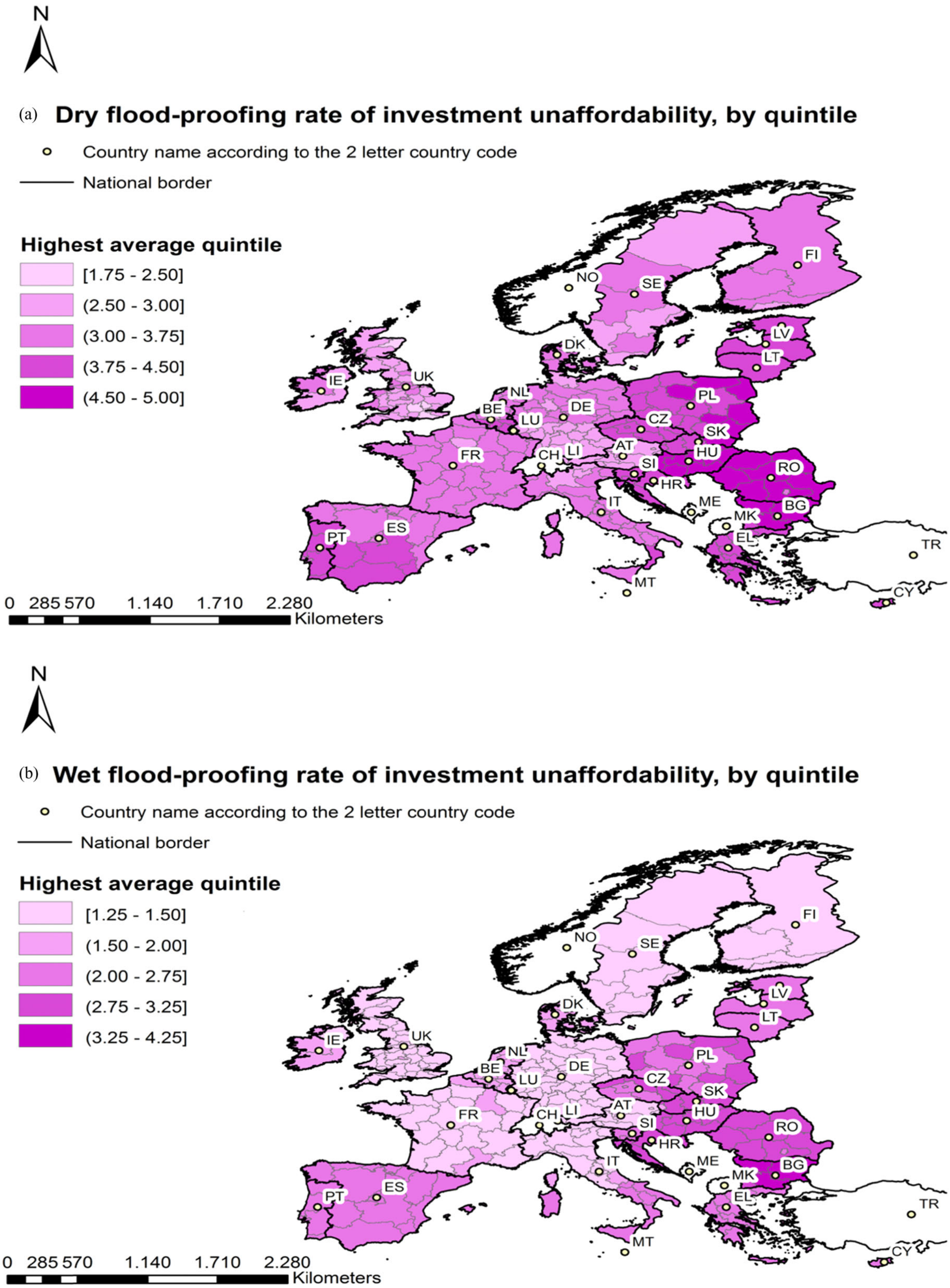

Fig. 2. The highest quintile for which flood-proofing is found investment unaffordable, on average across cost schemes, under the residual income definition.

Table II. The Rates of Investment Unaffordability under the Expenditure Definition of Unaffordability

	Cost Scheme 1	Cost Scheme 2	Cost Scheme 3	Cost Scheme 4	Average
		5% of income threshold			
Dry flood-proofing	99	99	99	99	99
Wet flood-proofing	97	98	99	99	98
		10% of income threshold			
Dry flood-proofing	99	99	99	99	99
Wet flood-proofing	80	84	99	90	88
		20% of income threshold			
Dry flood-proofing	96	98	99	99	98
Wet flood-proofing	48	43	99	62	63

Europe, on the whole, displays the highest rates of unaffordability of at least the 2nd income quintile.

3.1.2. Expenditure Threshold

The results presented in Table II show very high rates of unaffordability across the studied investment affordability thresholds. The nearly 100% rates under all cost schemes for dry flood-proofing highlight the financial burden if measures must be paid upfront. The significance of the burden can be seen from the threshold of 20% of disposable income required to bring the rate of unaffordability for wet flood-proofing below 50% for Cost Schemes 1 and 2, while still suffering from a significant burden for dry flood-proofing across all cost schemes presented in Table II.

Moreover, the rates of unaffordability under the expenditure definition are much higher than under the residual income differentiation. This difference occurs because the two definitions of affordability focus on different aspects of affordability. The residual income definition focuses on the lowest income members of society, as those below the poverty line will always be deemed to face unaffordable expenditures. The expenditure definition has a wider ranging scope due to its focus on a certain percentage of income, which allows everyone to contribute toward the costs of property-level adaptation measures.

3.2. Rates of Payment Unaffordability

Assuming the full uptake of loans, the rates of investment unaffordability are high under both definitions given that the measures must be paid for upfront. The introduction of low-cost loans reduces the highest quintile of unaffordability to the first quintile almost universally under the residual income definition for dry and wet flood-proofing. This is because the residual income definition produces a lower bound of unaffordability at the poverty rate, which was 16% on average across Europe in 2015. In percentiles, this implies a rate of unaffordability on average equal to 20% for dry flood-proofing and 17% for wet flood-proofing. This represents a reduction in unaffordability of nearly 71% for dry flood-proofing and 44% for wet flood-proofing under the residual income definition of unaffordability. The locations of these results are presented in Panel A (dry flood-proofing) and Panel B (wet flood-proofing) of Fig. 3.

The introduction of loans has a stronger impact on the rate of payment unaffordability under the expenditure threshold. The change in the rate of unaffordability due to the loans is, on average, 50%–94% for dry flood-proofing and 86%–99% for wet flood-proofing, across the cost schemes. Therefore, unlike under residual income thresholds of affordability, a policy focused on expenditure thresholds can have rates of unaffordability of nearly 0%, maximizing social access to adaptation measures.

Overall, the introduction of loans for property-level adaptation measures greatly improves the rates of affordability by replacing investment affordability with payment affordability as the relevant concept. This is in turn spread costs over time, resulting in a much smaller flow values. While Fig. 3 may not be surprising, in the sense the measures are more affordable, it highlights the very large difference between the rates of unaffordability under the different concepts. This is especially true concerning the various expenditure thresholds (Table III vs. Table IV). Therefore, potentially assuming that the residents of flood-prone areas have or do not have access to ways to finance the purchase of adaptation measures can have large implications for how strategies for promoting adaptation are developed. This is because

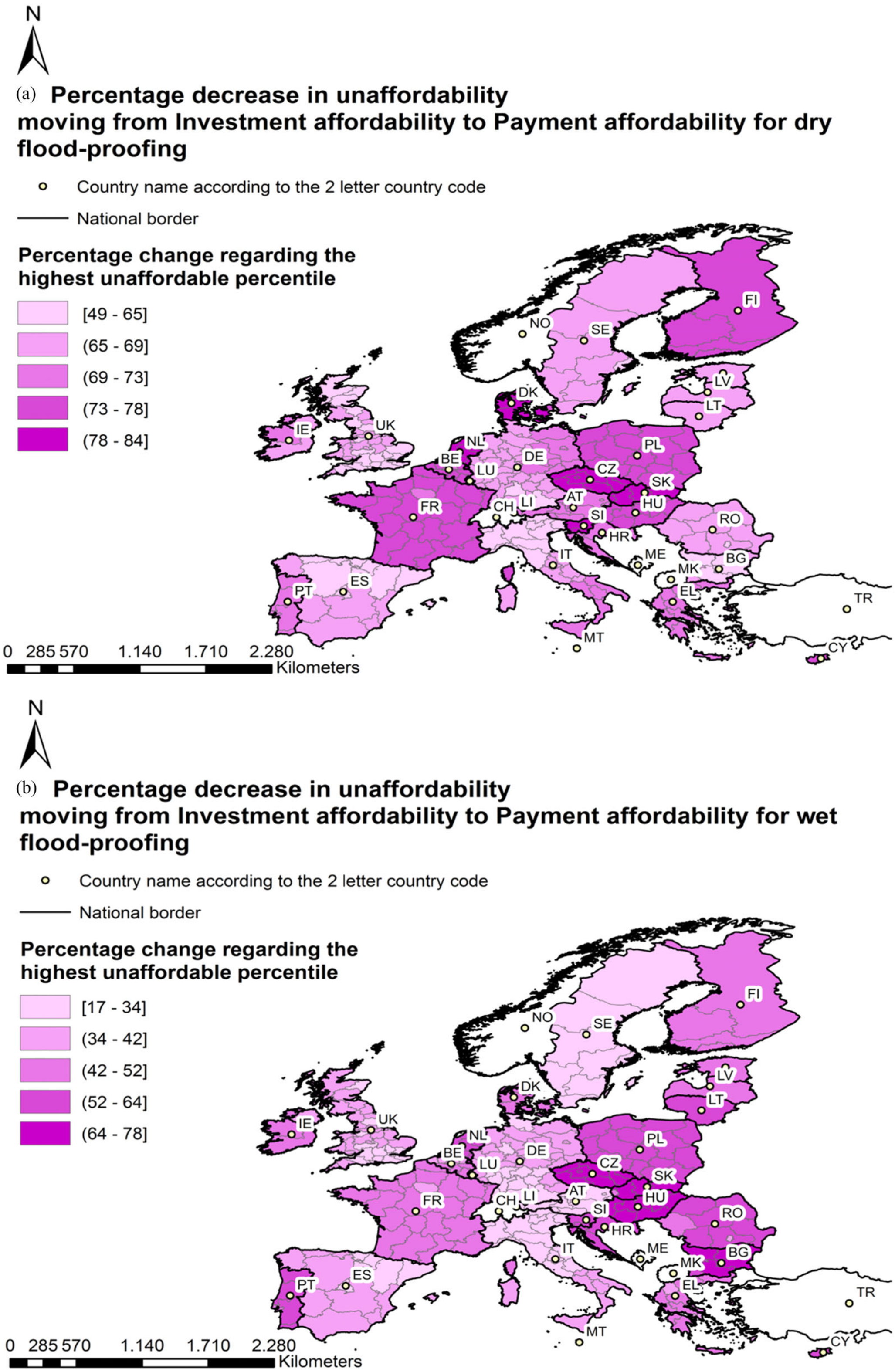

Fig. 3. Percentage change in the rate of unaffordability due to low-cost loans facilitating a movement from investment affordability to payment affordability under the residual income definition.

simply providing incentives such as insurance premium discounts for adaptation may only be effective for wealthy residents who can more easily finance purchases and recoup their expenditure through the measure's long-run benefits. This links back to fairness as it implies that without this consideration of reasonable contributions, the increase mandate of property-level action may only enhance differences in patterns of resilience across society.

3.3. 3 Sensitivity Analysis

3.3.1. Income Distribution Assumptions

A core assumption of this work is that the shape of national income distribution can be used as a proxy distribution for the various NUTS 2 regions within a country. This assumption is stronger for some countries than others. There are 6/28 countries that consist of a single NUTS 2 region. For the remaining countries, the number of NUTS 2 regions ranges from 2 (e.g., Croatia or Slovenia) to 39 (Germany), with an average of 12 regions per country. Therefore, the shape of the income distribution at the NUTS 2 may differ from the national distribution. It is also possible that these differences cancel out when aggregated. Thus, this study aimed to limit this uncertainty by focusing on the rate of unaffordability rather than the magnitude of unaffordability. The magnitude of unaffordability is the difference between the affordability threshold and expenditure. The magnitude of unaffordability may be more sensitive to the shape of the distribution as compared to the rate of unaffordability. This is because the rate as compared to the magnitude is not as concerned with the distance but rather simply that one is likely larger than the other.

However, the specific implications of this assumption may differ across the two affordability threshold definitions. Regarding the expenditure threshold definition with investment affordability, the rate of unaffordability covers nearly the entire income distribution. Therefore, it is quite likely that unless the shapes of the regional income distributions radically differ from the national, there will not be a large difference in the final rate of investment unaffordability. The same is likely true for payment affordability, when higher income thresholds are used. For example, at the 10% of income level, the rate of payment unaffordability is nearly 0% for wet floodproofing. Such low rates of unaffordability also indicate a relative degree of insensitivity to the shape of the income distribution.

Concerning the residual income threshold definition, an important note is that this threshold has a fixed minimum rate that is equal to that defined by the relative poverty rate. This rate was at 17% at the EU level in 2015. Similar to the rate of payment affordability under the expenditure definition, it is similarly insensitive to the shape of the distribution as this definition is predominantly focused on the bottom end of the income distribution. This can be seen how the rates of payment unaffordability closely mirror the rates of relative poverty, as everyone below this cutoff point will find the measure unaffordable as well as those reasonably close to it.

Finally, the influence of this source of uncertainty on the resulting implications is limited at the scale of this study. This is because of the focus on the rates of unaffordability and the use of varying definitions and thresholds for affordability. When taken together, the individual findings repeat how the rates of unaffordability are much lower when there are cost-spreading mechanisms in place, in turn helping to ease social justice concerns by promoting fairer access to risk reducing measures. Moreover, while the calibrated distributions are a rough measure suitable for the current scale of the analysis, more detailed information will be required to establish suitable policy mechanisms at the local level.

3.3.2. Cost Assumptions

The assumptions made in Section 2.1.2 regarding adaptation costs did not take into account the varying economic conditions of the countries. Therefore, two additional price adjustment steps are taken. One adjusts the costs according to the ratio of domestic prices relative to the European average in 2015 (Eurostat variable ID: *tec00120*) accounting for different price levels. The second adjusts by differences in labor costs relative to the European average (Eurostat variable ID: *lc_lci_lev*), as labor costs can be considered as an important cost element. This can result in significant changes to the measures costs. For instance, Bulgaria is associated with labor costs 83% lower than the European average, or a price level 53% of the European average. Denmark on the other hand is associated with labor costs 59% larger than the European average or a price level 34% larger than the European average price level. The implications of these changes are presented in Table III for

Table III. The Average National Rate of Investment Unaffordability across Cost Schemes under Various Price Adjustments

	Baseline Costs (Table I)	Adjustment via Labour Cost Index	Adjustment via Relative Price Level Index
		Expenditure Definition	
		5% of income threshold	
Dry flood-proofing	99	99	99
Wet flood-proofing	98	96	98
		10% of income threshold	
Dry flood-proofing	99	99	99
Wet flood-proofing	88	81	88
		20% of income threshold	
Dry flood-proofing	98	96	98
Wet flood-proofing	63	44	56
		Residual income definition	
Dry flood-proofing	78	68	75
Wet flood-proofing	47	38	42

Table IV. The Average National Rate of Payment Unaffordability across Cost Schemes under Various Price Adjustments

	Baseline Costs (Table I)	Adjustment via Labour Cost Index	Adjustment via Relative Price Level Index
		Expenditure Definition	
		5% of income threshold	
Dry flood-proofing	50	28	41
Wet flood-proofing	14	6	9
		10% of income threshold	
Dry flood-proofing	21	6	11
Wet flood-proofing	4	1	1
		20% of income threshold	
Dry flood-proofing	6	1	3
Wet flood-proofing	1	0	0
		Residual income definition	
Dry flood-proofing	21	20	20
Wet flood-proofing	19	18	18

investment affordability and Table IV for payment affordability at the national level.

Taking investment affordability first, under the expenditure definition, the 5% and 10% income thresholds result in relatively minor changes in the rate of investment unaffordability that remain over 80%. Under the 20% of income threshold, wet flood-proofing displays a significant drop (up to 20 percentage points). However, it remains at least 44%. The residual income definition also displays a significant change from 78% to 68% for dry flood-proofing and 47% to 38% for wet flood-proofing. While significant changes occur, the overall implication remains the same, in that, a substantial percentage of people across Europe would face affordability issues.

Regarding payment affordability, expenditure-based definitions display large changes. When 5% of income is used as the threshold, rates of payment unaffordability fall by ~50%, when 10% of income is used, rates fall by ~71%, and fall by nearly 100% when a threshold of 20% of income is used. There is a much smaller change when residual income is used to judge affordability as the rates of payment affordability fall by a single percentage point. However, these rates are still 71% lower in the case of dry flood-proofing and 53% in the case of wet flood-proofing. Therefore, the core implication remains the same.

3.3.3. Use of Upper Bound Cost Estimates

Using the upper cost estimate (for the three cost schemes available) alters investment unaffordability little as the measures are unaffordable for the majority of households. The results for payment affordability change depending on the affordability threshold. Under the residual income threshold, payment unaffordability is, on average, 26% for both dry and wet flood-proofing. Under the expenditure threshold (of 20% of income), the rate of unaffordability grows to 21% for dry flood-proofing and 22% for wet flood-proofing. However, these rates of payment unaffordability are still much lower than for investment unaffordability, further indicating the importance of cost-spreading mechanisms.

3.3.4. Role of Savings

Savings are a stock variable that can support income in purchasing adaptation measures. Data on the median savings rate per income quintile (Eurostat variable ID: *icw_sr_03*) show substantial differences across groups. The European average for the first income quintile has a savings rate of −0.12 while the top quintile's value is 0.36. However, a weakness of these data is that the total savings available to a household is unknown, as only a portion of a single year's income is assumed to be saved.

The results under the residual income threshold are unaffected, as the majority of households around the poverty line have negative saving rates, indicating little savings to contribute toward investment affordability. Moreover, as a relative threshold, it can also be understood that the financial resources of the purchaser should not be reduced to that of 60% of the median purchaser. Under the expenditure threshold, expenditure on property-level adaptation should not exceed savings plus the selected income threshold. Assuming a 5% threshold of disposable income, the highest average quintile finding dry flood-proofing unaffordable is 4.5 and for wet flood-proofing, it is 3.25, when savings are included. The use of a 20% income threshold lowers these values to 4.25 and 2.75, respectively. For dry flood-proofing, this represents a rate of unaffordability that is 10%–15% lower than when savings are excluded and 31%–35% lower for wet flood-proofing.

Overall, the inclusion of additional financial resources can have an effect on investment affordability under the residual income threshold but a much larger effect under the expenditure threshold. However, while this analysis is rather simplified, it does indicate that rates of investment unaffordability may be overestimated, at the top of the income distribution, due to greater access to financial resources as households become wealthier.

3.4. Integrated Flood Risk Management Implications

There is a large difference between the rates of unaffordability across definitions due to the difference between having access to financing mechanisms and not. Therefore, access to financing should be more readily considered as part of fair flood risk management action and research. Hence, assuming that such mechanisms are in place can be misleading on what we expect people to be able to contribute in a fair manner. More formally looking at affordability in regard to all aspects of flood risk management can help to refine these policy objectives. However, the formalization affordability, as applied to property-level adaptation measures, is a new aspect of flood risk management. It is possible that better understanding the individual-level construction of the cost-appraisal elements of Protection Motivation Theory (Bubeck, Botzen, & Aerts, 2012) could offer insights into how to better operationalize affordability based on how people subjectively perceive costs. Developing these insights with stakeholder input results in definitions that suitably reflect local social expectations.

The study results indicate that investment affordability is problematic across all of Europe. However, the burden this imposes is nearly eliminated under the expenditure threshold definitions and falls to the, nearly, lowest rate possible under the residual income definition. Therefore, this movement toward individual action should be accompanied with mechanisms to ensure that sufficient resources or financing mechanisms are made available. This is in order to make sure all households have sufficient access to financial resources if needed. Additionally, if this outcome is achieved via loans, then the repayment schedule also provides a reminder to the property owner of the adaptation measure and the required maintenance.

The proposed loans can be made available to those for whom adaptation measures are investment unaffordable. Moreover, providing low-cost loans also achieves a social objective in making sure that lower income households have access to loans, which may not be possible under full private market conditions (National Research Council, 2015). While low-cost loans generate higher rates of affordability, the effect's magnitude differs across affordability threshold definitions. Therefore, if thresholds similar to the residual income threshold are used, then policymakers may need to couple the loans with additional mechanisms (e.g., vouchers) to provide equal adaptation opportunities to those who are beneath the poverty line. Such mechanisms can be connected to preexisting welfare payments. Moreover, the system may require a degree of flexibility around the point at which loans are provided. This is because households may be labelled as requiring assistance just because they live in a generally wealthy environment, because of changing patterns of income inequality, for example. Therefore, effects to incentivize the adaptation should have mechanisms to help provide suitable assistance to ease one avenue through which property-level adaptation is limited. Other measures may be required to stimulate demand for these measures in the first place. Linking such concerns is a natural extension of integrated flood risk management, which seeks to create a suitable enabling environment for risk reduction across all actors (Bubeck et al., 2017).

An implicit assumption made is that the suggested loans are provided by a public sector organization in order to provide suitable support for people to adapt. However, public resources may be scarce and, even though with loans some of the program costs are recouped, resources may not be available. Therefore, there is scope for collaboration in public–private partnerships (PPPs) to provide these loans. PPPs are argued to be useful in the disaster insurance space (Kunreuther, 2015). Through closer collaboration, additional resources and experiences can be leveraged to address the complex issues of how the residents of flood-prone areas can contribute to flood risk management. This approach is similar to the elevation certificates offered for flood insurance premium discounts as part of the National Flood Insurance Program in the United States (Aerts et al., 2013). The above is one possible mechanism to increase the affordability of property-level adaptation measures that are often mentioned in the literature (e.g., Botzen & van den Bergh, 2008; Montgomery & Kunreuther, 2018). However, flood risk management takes place at the national or subnational level. This means that flood risk management can be considered as a result of public policy choices (Hudson, Botzen, & Aerts, 2019; Surminski, 2017), rendering it likely that there is not a one-size-fits-all solution (Surminski et al., 2015) and as such, risk managers can compare the suitability of a range of alternative mechanisms given the needs and preferences of local stakeholders. For instance, the first alternative is "flood risk mitigation grants," whereby the resident directly receives funds for property-level adaptation. This strategy addresses affordability by rendering measures investment affordable and therefore do not need their costs to be spread over time. This has the implications of social transfer. This in itself is not necessarily problematic as a result of policy choices. However, the resources spent will only be recouped in a social sense through lower flood damage. This could be problematic depending on the social transfer required. However, it is not possible, a priori, to establish the total size of these transfers as they depend on uptake rates, the particular measures employed, etc. A loan system, on the other hand, mitigates some of these social transfers through loan repayments. A further relative of a loan system could be the resulting endowment effects, which is where the owner values measures more because they own the product (Ericson & Fuster, 2014), which can help with the maintenance of flood-proofing measures they have purchased rather than one "gifted" via a grant.

An additional alternative to loans in moving from investment to payment affordability is zoning regulations. Zoning regulations for flood risk management can require that all new buildings in flood-prone areas, if development cannot be redirected, are mandated to integrate property-level measures into their construction process (Burby, 2001; Burby, Deyle, Godschalk, & Olshansky, 2001; Hudson & Botzen, 2019). This mechanism places the cost of the measures as a relatively small portion of the property cost, as it is cheaper to build these measures into new property rather than retrofitting existing property (Aerts et al., 2013). Therefore, their cost will be annualized either as mortgage or rental payments. This approach brings two advantages; adaptation no longer requires a proactive choice overcoming several behavioral heuristics by shifting the responsibility to a smaller number of property developers. The second is that by connecting these payments to housing prices, in effect, it can be connected to preexisting welfare systems aimed at aiding people who find their housing costs unaffordable. A weakness is that it is most applicable to new buildings, whereas redirecting development in flood prone is a more productive avenue for limiting flood impacts and it requires the zoning regulations to be enforced.

Additionally, in each of the three above mechanisms social transfers are a component either directly, via loans or grants, or indirectly, via the welfare system. These transfers can also be seen as a needed requirement of a greater focus on individual-level action in flood risk management in order to make sure that all of society can take part in risk management as called for in the sustainable development goals (SDGs) or Sendai Framework.

A final consideration is moral hazard if the employed mechanism promotes a negative behavioral change could be promoted. For instance, encouraging more lower income households to reside in flood-prone areas, however, this is unlikely to be a significant problem if measures that are known to be cost-effective are focused upon. This increases the likelihood of a positive net impact through increased risk reduction measure employment rates, especially if this activity is considered as part of a wider integrated flood risk management plan. Additionally, there is a possibility that the respondent may not use the loan or grant for the stated purpose. This could be mitigated by directly transferring to the organization that installs the adaptation measures when support is requested (similar to household-level insulation upgrades in the United Kingdom for example).

4. CONCLUSION

The movement toward integrated flood risk management places greater obligations on the residents of flood-prone areas to reduce risk through proactive adaptation. However, this additional requirement requires that the burden imposed on households be assessed. This is to aid in developing the use of fair flood risk management metrics for a range of adaptation strategies outside of insurance to more widely integrate social justice metrics into flood risk decision making.

This article seeks to begin this assessment by extending the study of fair flood risk management principles via the affordability of property-level adaptation measures across Europe. This was achieved by combing information on property-level adaptation costs with interpolated income distributions across two different concepts of affordability and affordability thresholds. It was found that in terms of investment affordability, property-level adaptation measures are not affordable. However, payment affordability is much higher, thereby highlighting the benefits of developing strategies that spreads expenditures over time. Therefore, these mechanisms should be more actively considered within flood risk management and research.

The main implication is the importance of addressing the needs of vulnerable populations to produce a fair or just outcome for flood risk management. Vulnerable populations face disproportionate subjective flood impacts and also have a limited capacity to limit these impacts. The limited capacity to adapt is problematic for additional obligations imposed through integrated flood risk management approaches. This movement requires a greater focus on fair flood risk management principles so that all those threatened by, and mandated to act against, flooding are able to act. The concept of affordability can act as a metric of "fair" contributions to identify those who face difficulties and require additional support to achieve fair flood risk management outcomes. The results indicate the need for payment affordability to be the widely applicable concept in both policy and research. Once a suitable threshold is determined, the provision of low-cost loans is a potential mechanism to render adaptation affordable under this concept. However, achieving this outcome depends on specific public policy choices. Therefore, other mechanisms such as grants or the better integration of property-level adaptation measures into zoning policies and preexisting welfare systems maybe be locally preferred methods for achieving this outcome.

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