How high to elevate a house to manage deeply uncertain flood risks?

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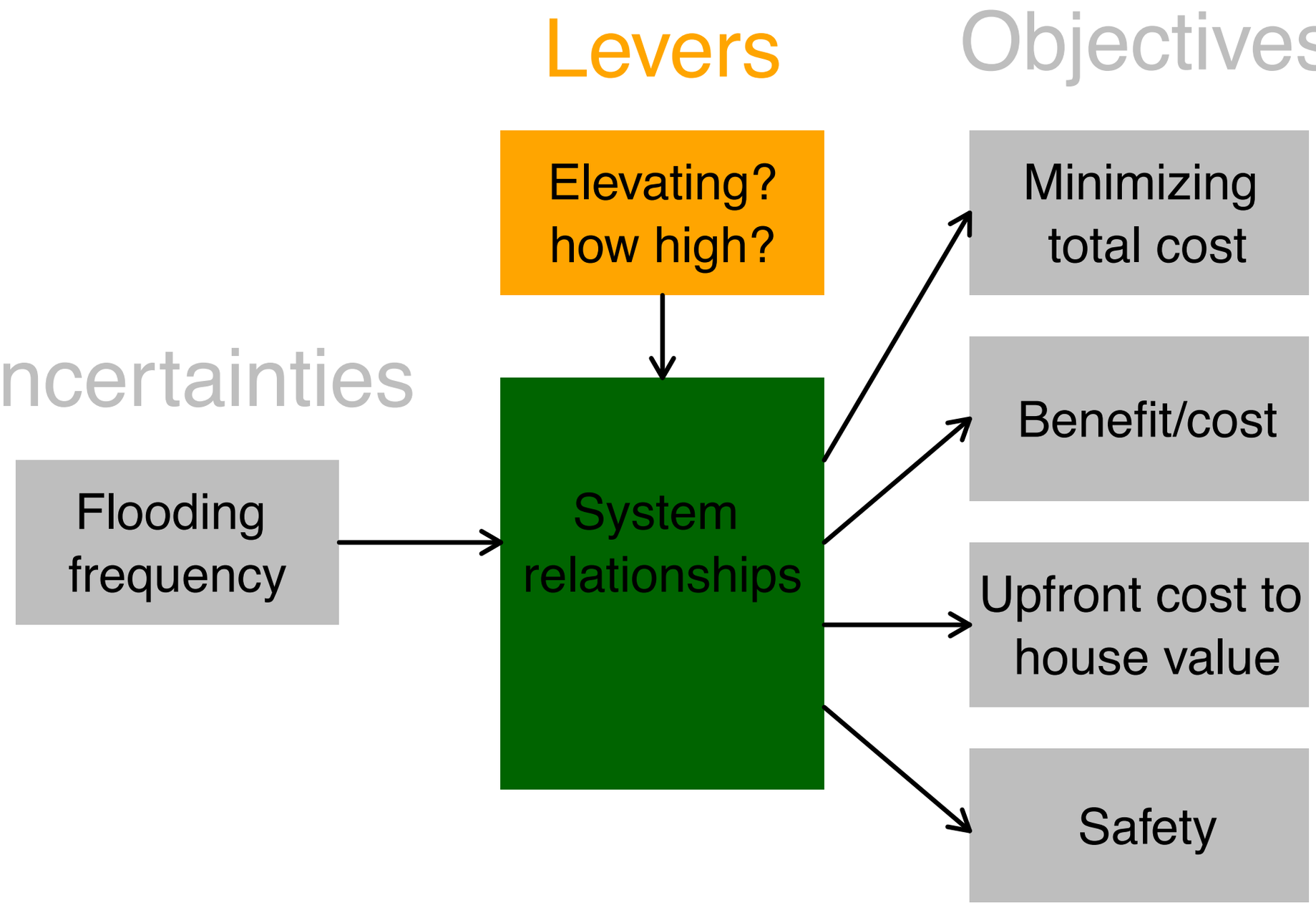
The decision of elevating a house

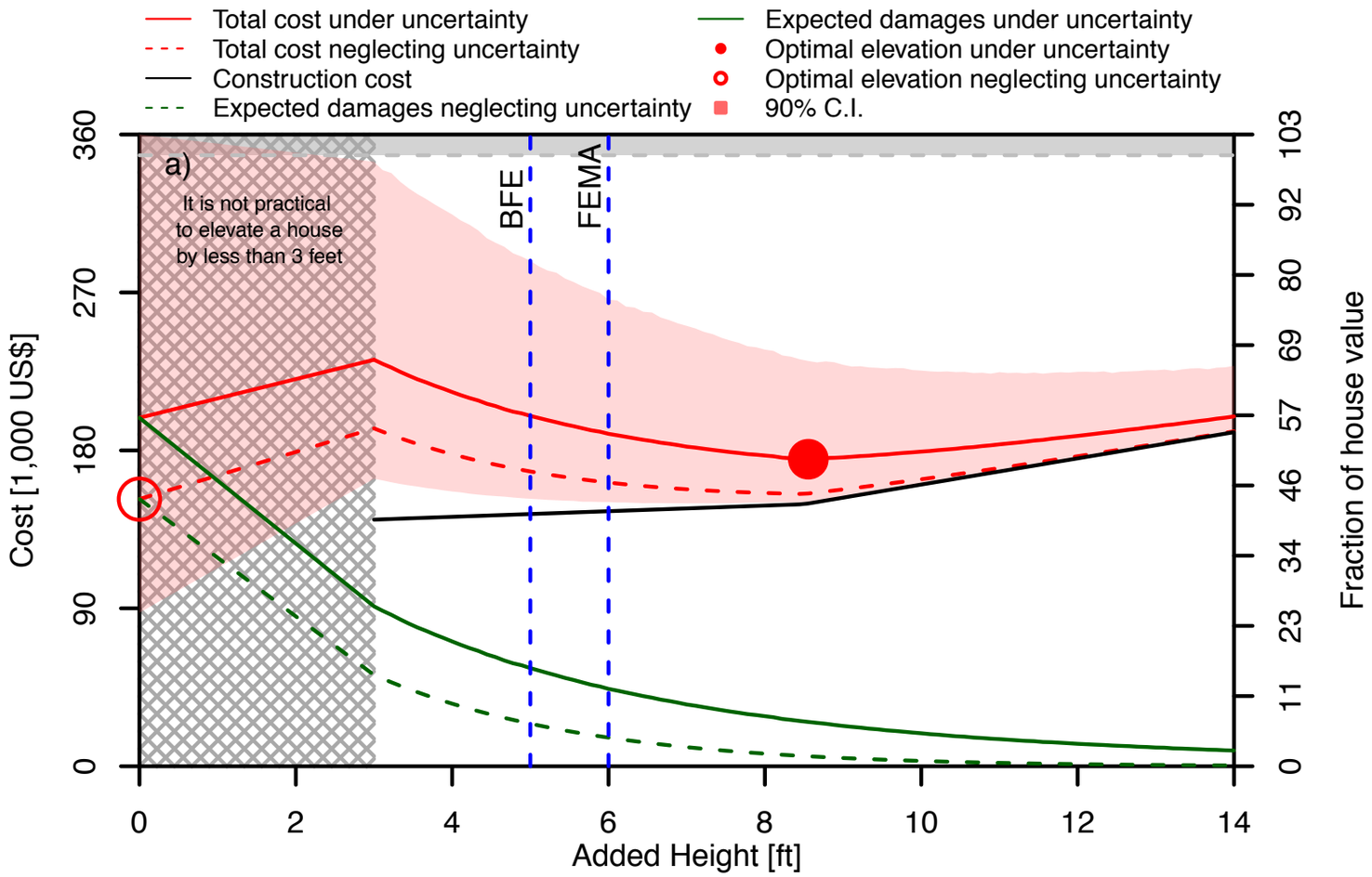
- What are the levers?
- Is this a single or multi-objective decision?
- What are the objectives?
- What uncertainties affect the decision?
- What are the trade-offs?

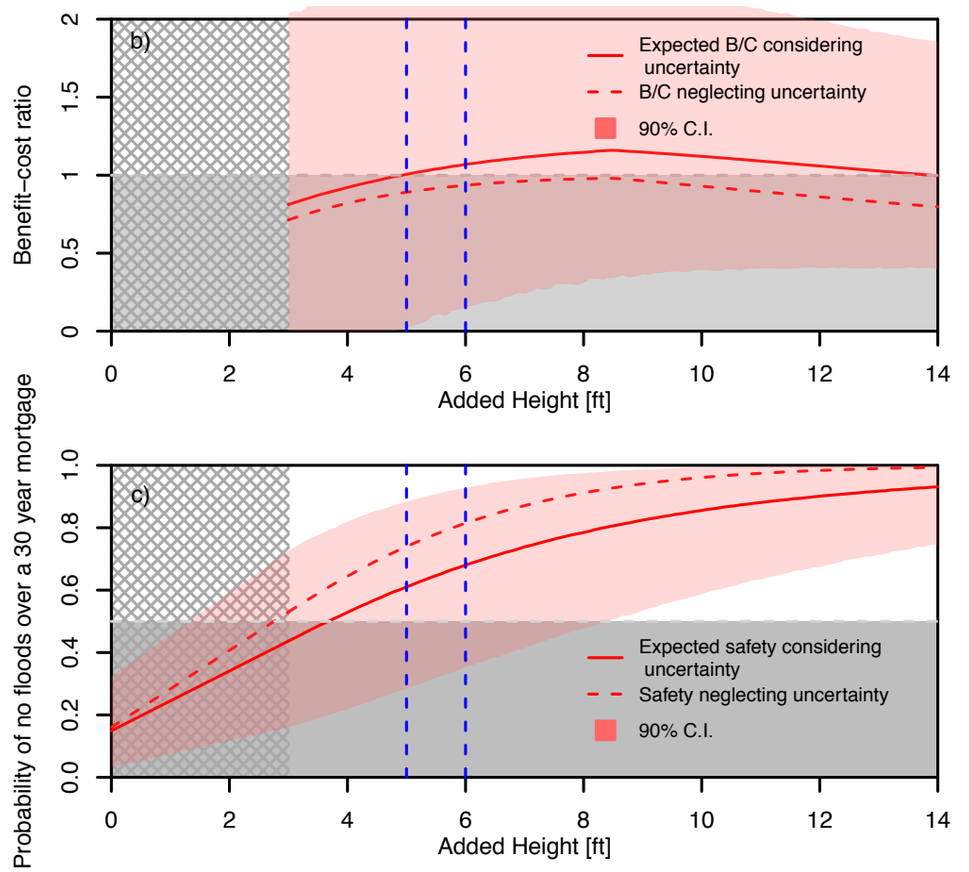
What variables are involved in this decision? What are the objectives? what uncertainties affect the decision?



The XLRM diagram for the decision of elevating a house. Uncertainties include flooding frequency which depend on the annual maximum flood distribution and its parameters. Objectives of such a decision include minimizing the total cost, maximizing the benefit to cost, minimizing the ratio of the upfront cost to initial house value, and maximizing the safety which is the probability of no floods during the house's lifetime. The overall levers of this decision is the added height to the house and the decision of whether elevating or not.

Is it worth to elevate a typical house in Selinsgrove, PA?

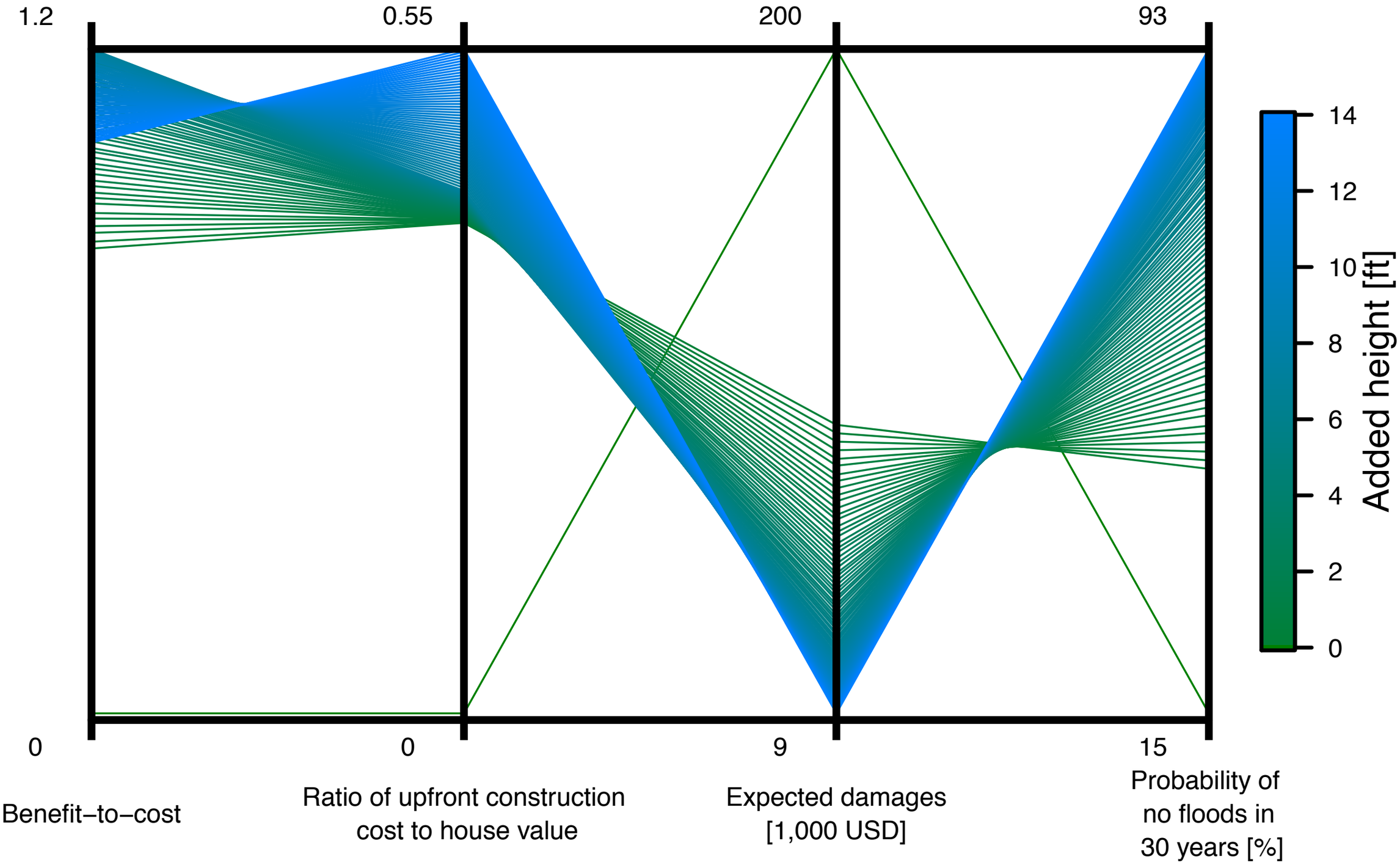




Analysis of objectives for a typical house is Selinsgrove, PA. This house is 1,500 square feet with a value of 350,000 US$ that is 5 feet below the base flood elevation. The lifetime of this house is 30 years. a: Total cost, damages, and construction cost for various heightening scenarios. The hatched area indicates impractical heightening scenarios of less than 3 feet. The base flood elevation and FEMA's recommendation are shown via dotted blue lines. b: The b/c ratio for all heightening scenarios. c: safety for all scenarios. Please note that safety is defined as the probability of no floods during the house's lifespan.

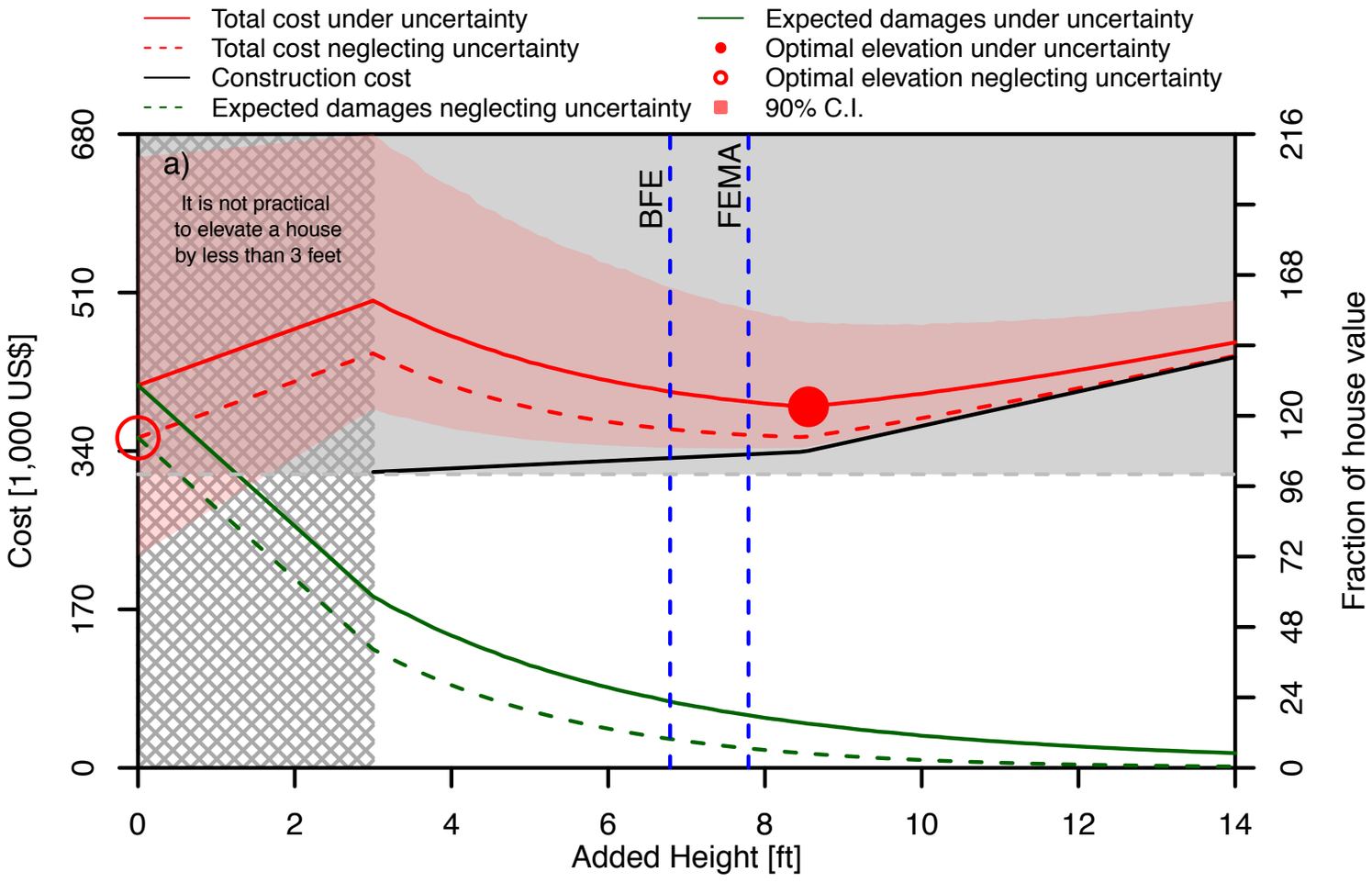
- **By ignoring the uncertainty in flooding frequency it is not worth to elevate this typical house; however, by considering uncertainty, it is worth it.**
- **Considering uncertainty changes the decision of elevating a house**

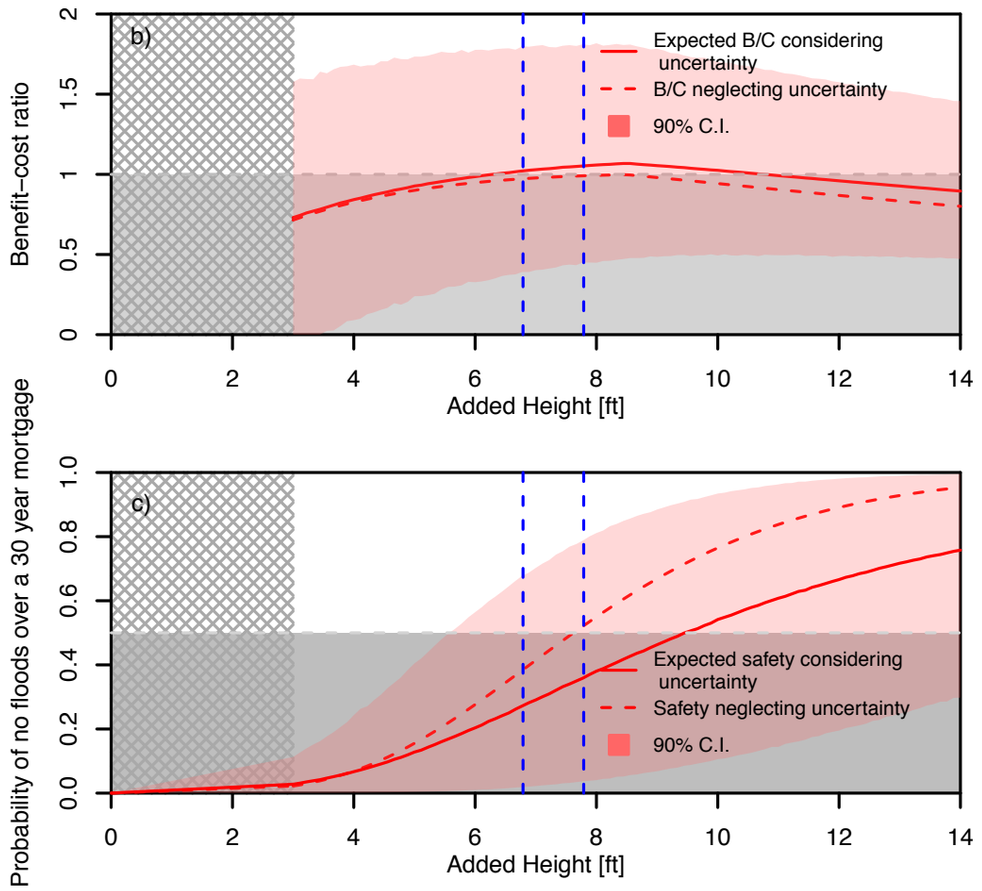
What are the trade-offs for a typical house in the area?



Parallel plot of objectives for different heightening scenarios. Each vertical line indicates an objective and each line indicates a heightening scenario. The scenarios are color-coded according to the colorbar on the right. The separate green line maps objectives for “not elevating” scenario.

Sometimes, for elevating a house to optimal elevation under uncertainty, the homeowner needs to spend more money then the initial house value



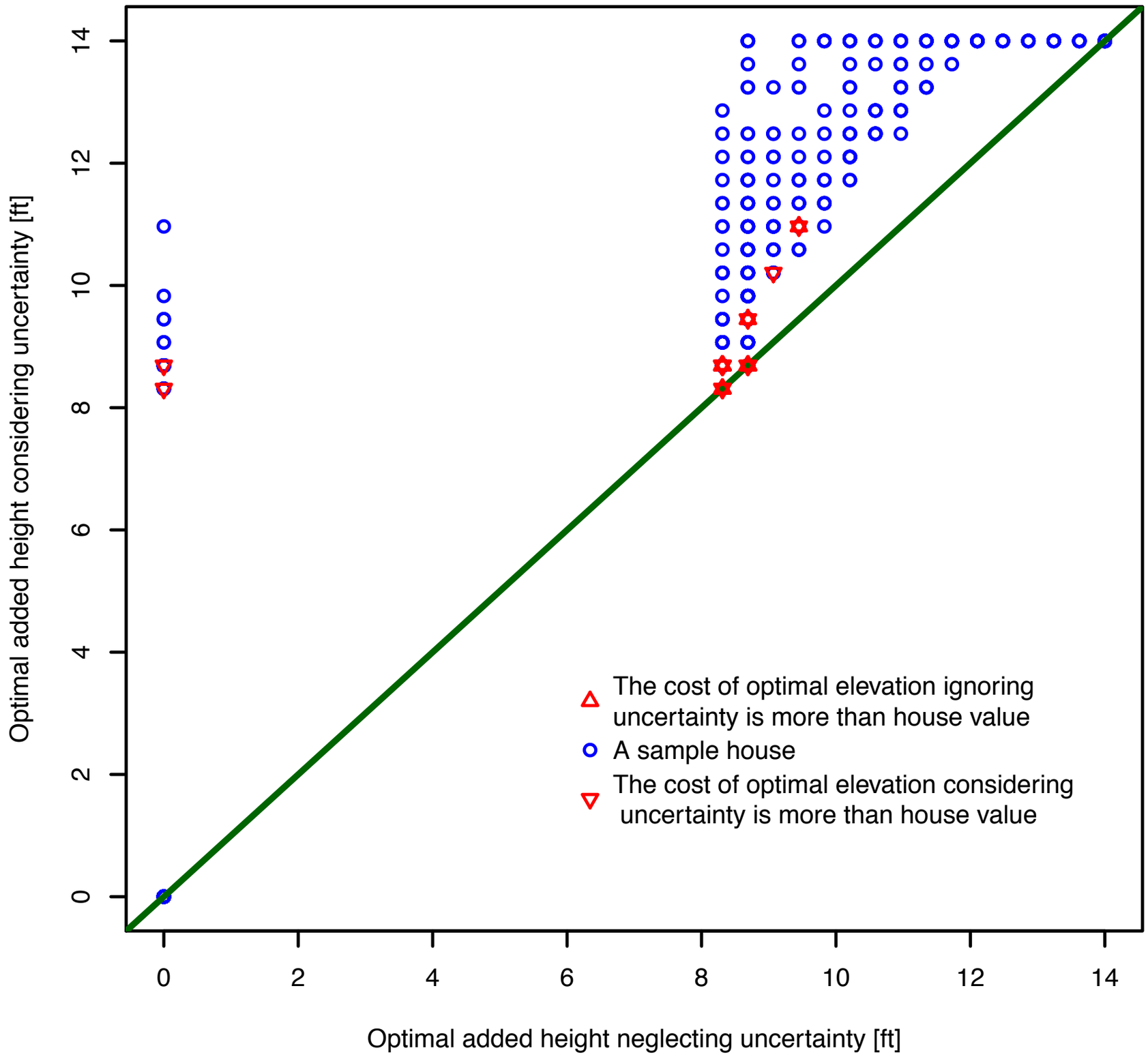


Analysis of objectives for a house is Selinsgrove, PA where considering uncertainties in flooding frequency changes the decision. This house is 3,700 square feet with a value of 316,330 US$ that is 6.7 feet below the base flood elevation. The lifetime of this house is 95 years. a: Total cost, damages, and construction cost for various heightening scenarios. The hatched area indicates impractical heightening scenarios of less than 3 feet. The base flood elevation and FEMA's recommendation are shown via dotted blue lines. b: The b/c ratio for all heightening scenarios. c: safety for all scenarios. Please note that safety is defined as the probability of no floods during the house's lifespan.

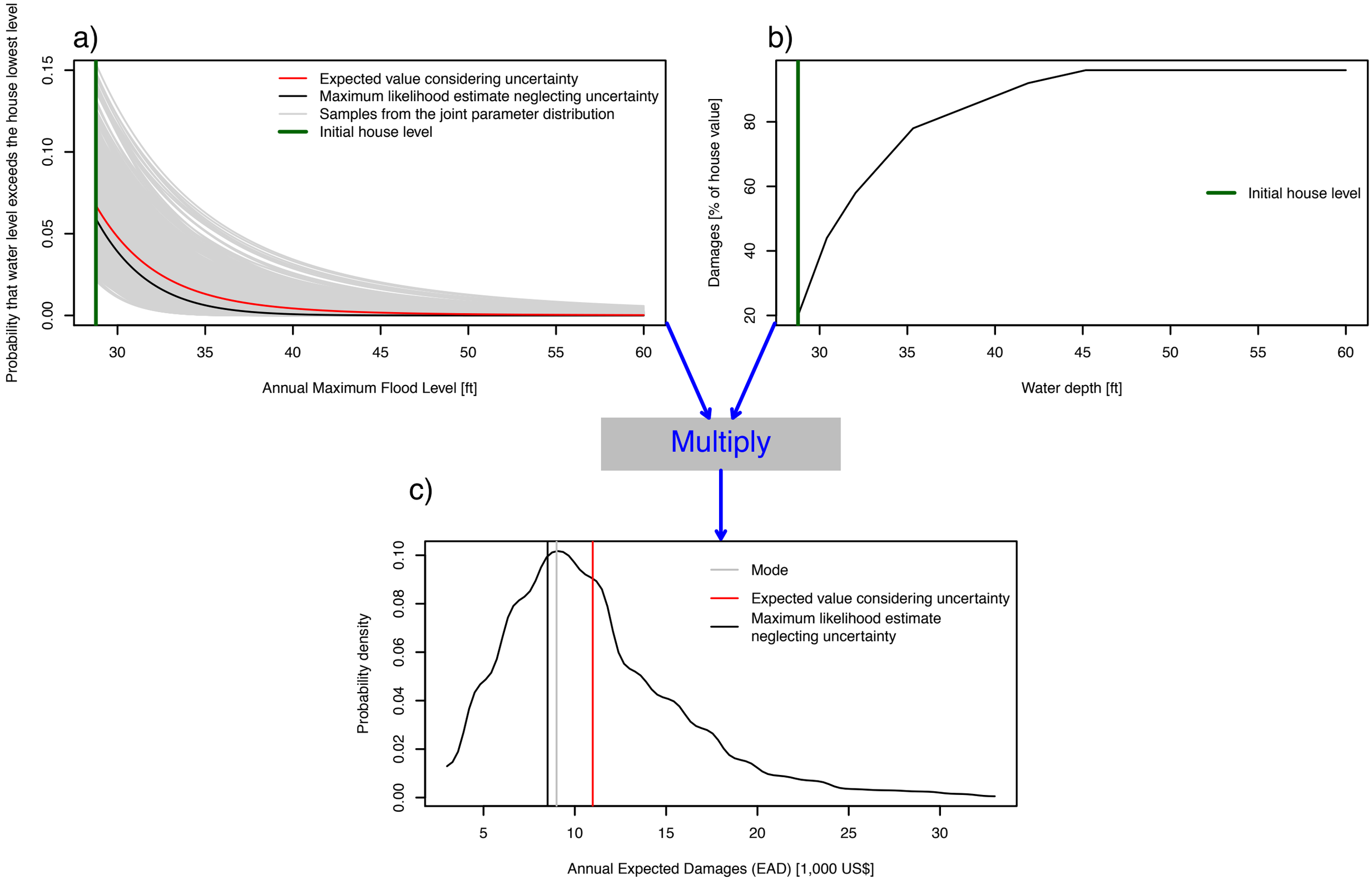
Is uncertainty important in this decision?

- What are the uncertainties involved in this decision?
- Which uncertainty source is the most important source?
- What do trade-offs look like considering uncertainty?
- How does the optimal elevation change under uncertainty?

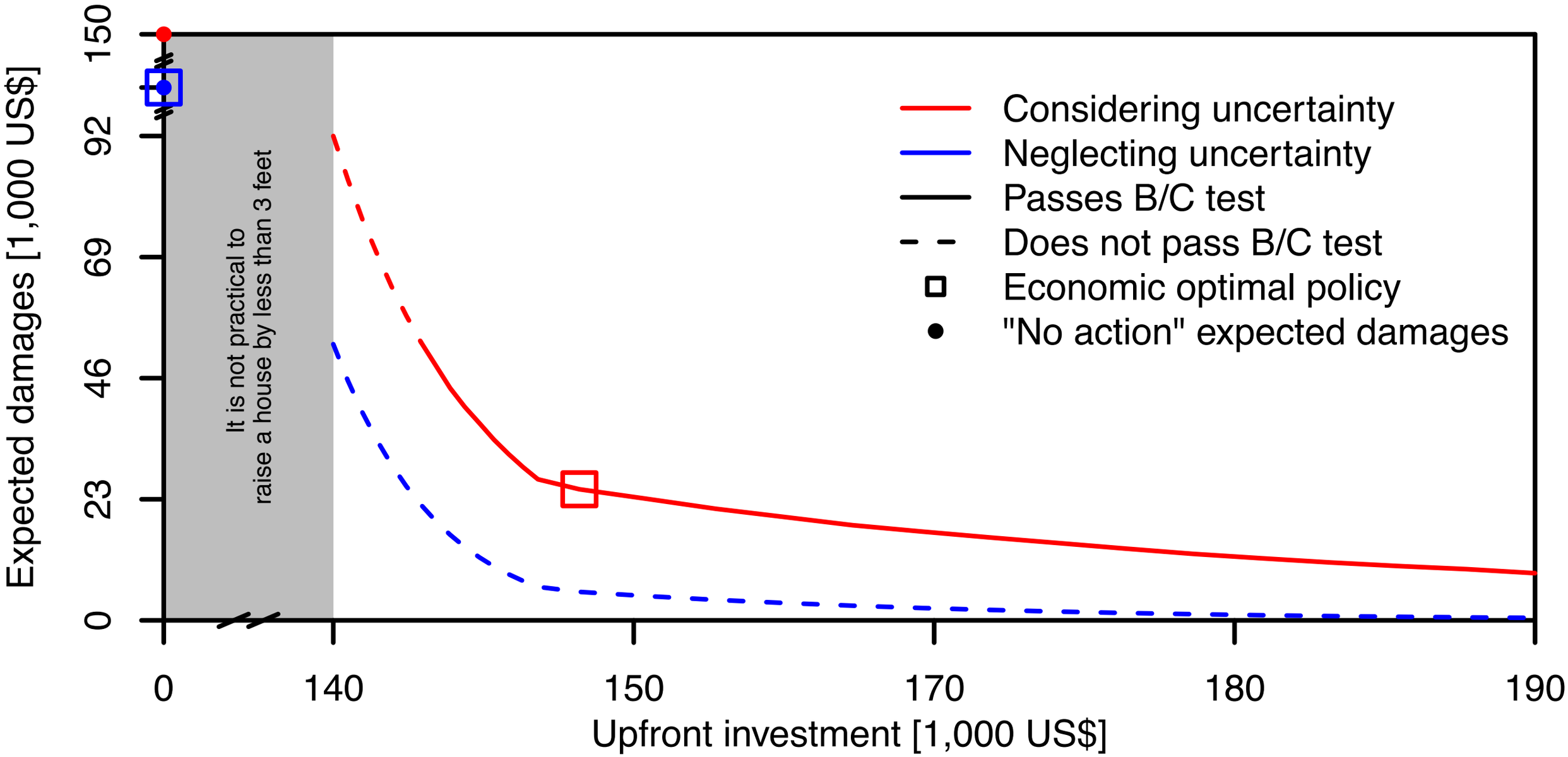
In all cases, the optimal elevation under uncertainty is greater than (or equal) the optimal height neglecting uncertainty



Considering uncertainty results in higher expected damages

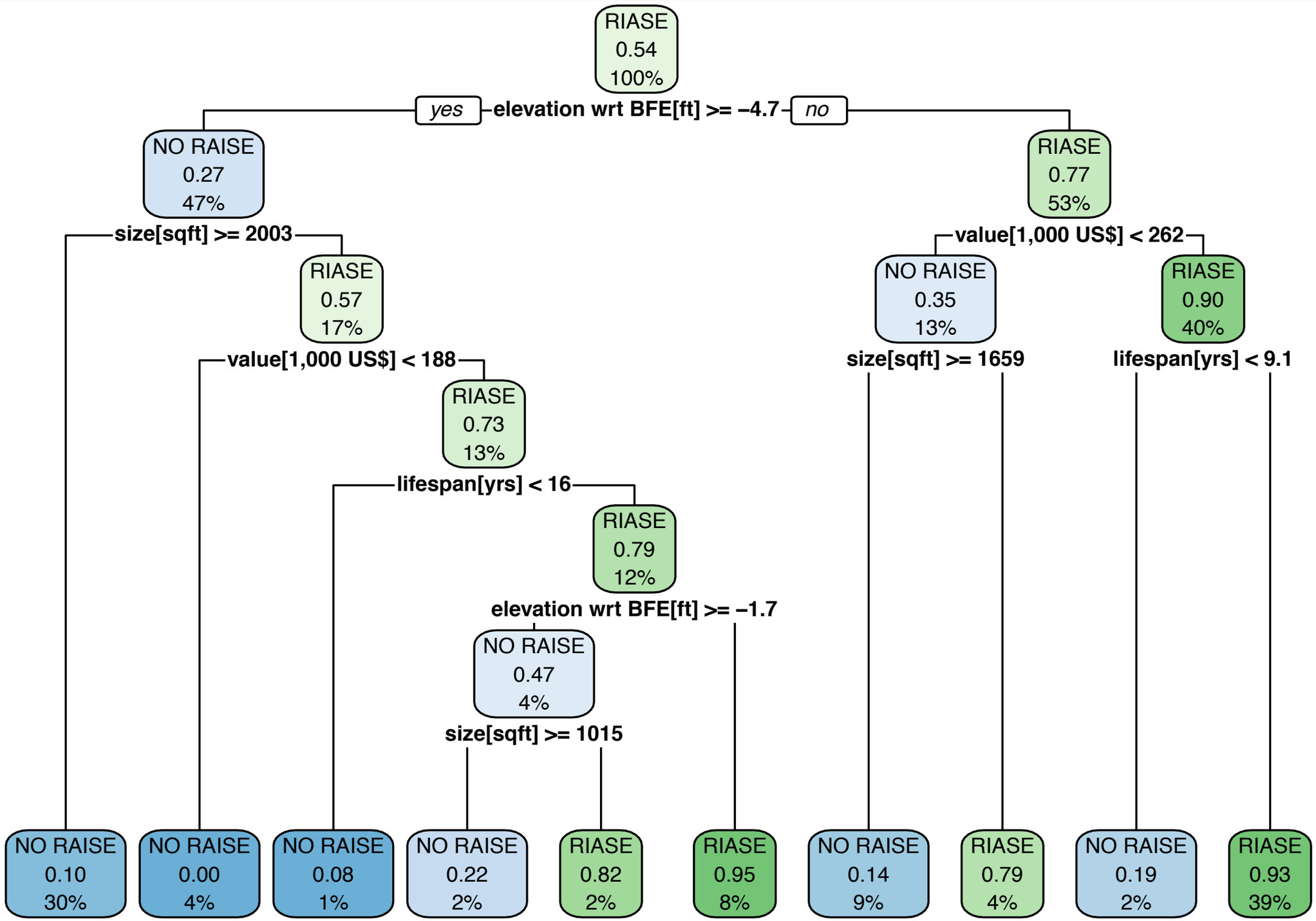


Trade-offs between construction cost and expected damages are impacted by uncertainties



Trade-offs, with and without considering uncertainty for a typical house in Selinsgrove, PA. House size=1,500 sqft; House elevation with respect to the base flood elevation= -5 feet; House value= 350,000 US$; lifespan=30 years.

What are the characteristics of the houses that should be elevated?
1. Elevating big cheap house whose lowest floor elevation is close to the BFE does not

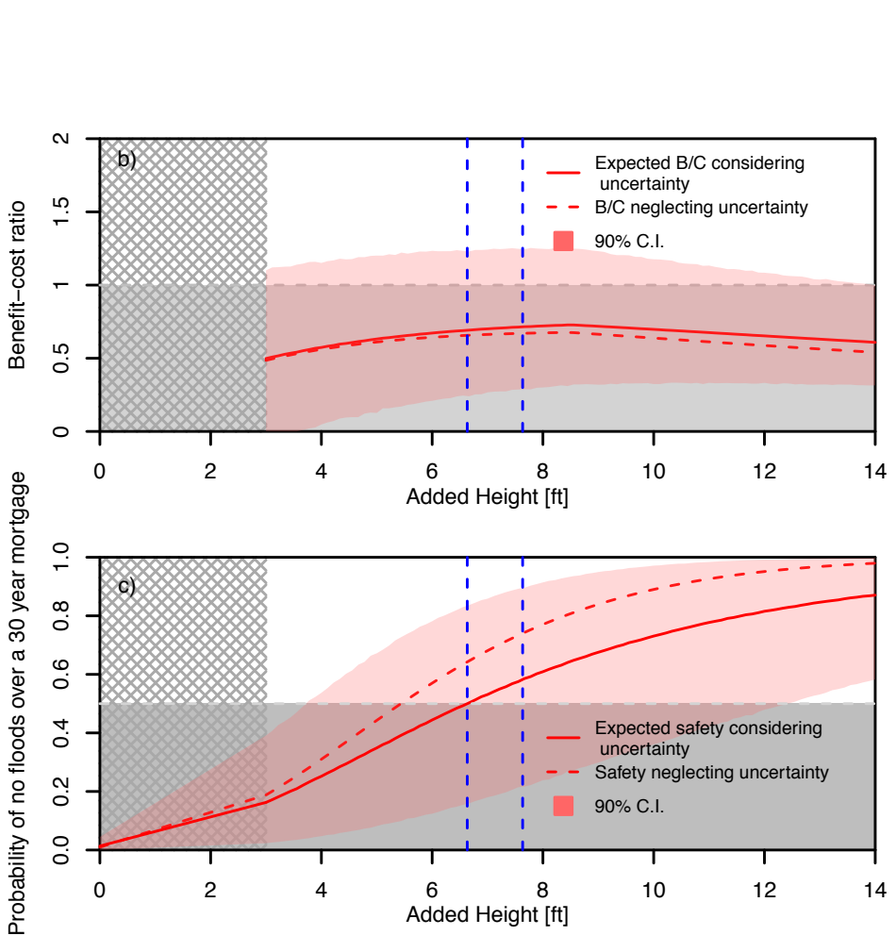


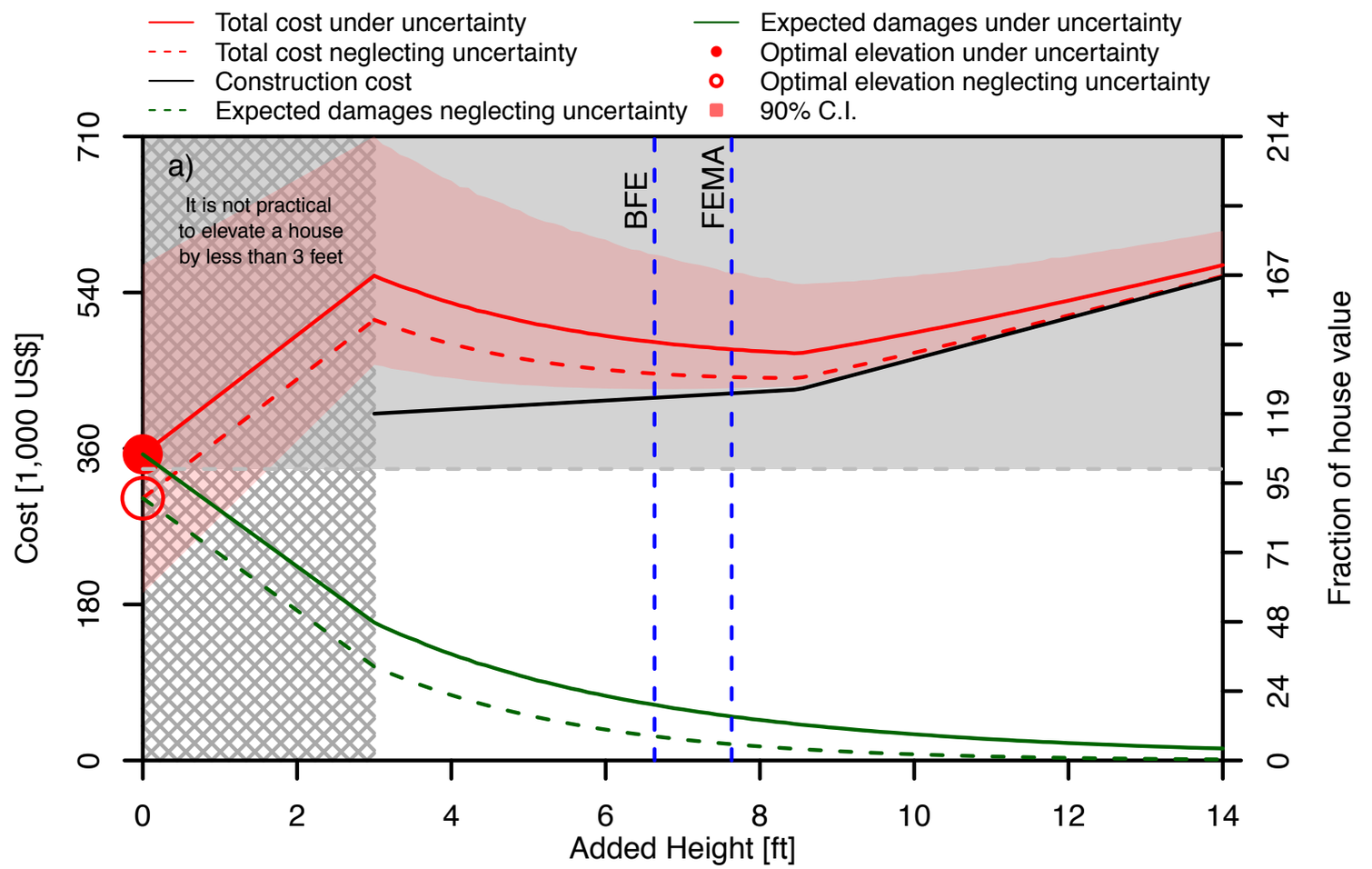
CART diagram for the hypothetical community. In calculation of the optimal elevation, uncertainty is considered

FEMA recommends elevating the house to 1 foot above the base flood elevation

- Is FEMA's recommendation cost optimal?
- Is FEMA's recommendation cost effective?
- Does FEMA over-estimation or under-estimation the optimal elevation?
- What are the characteristics of houses where FEMA's recommendation is not cost optimal or cost effective?

Sometimes, elevating a house to FEMA's recommendation means spending more than the current house value

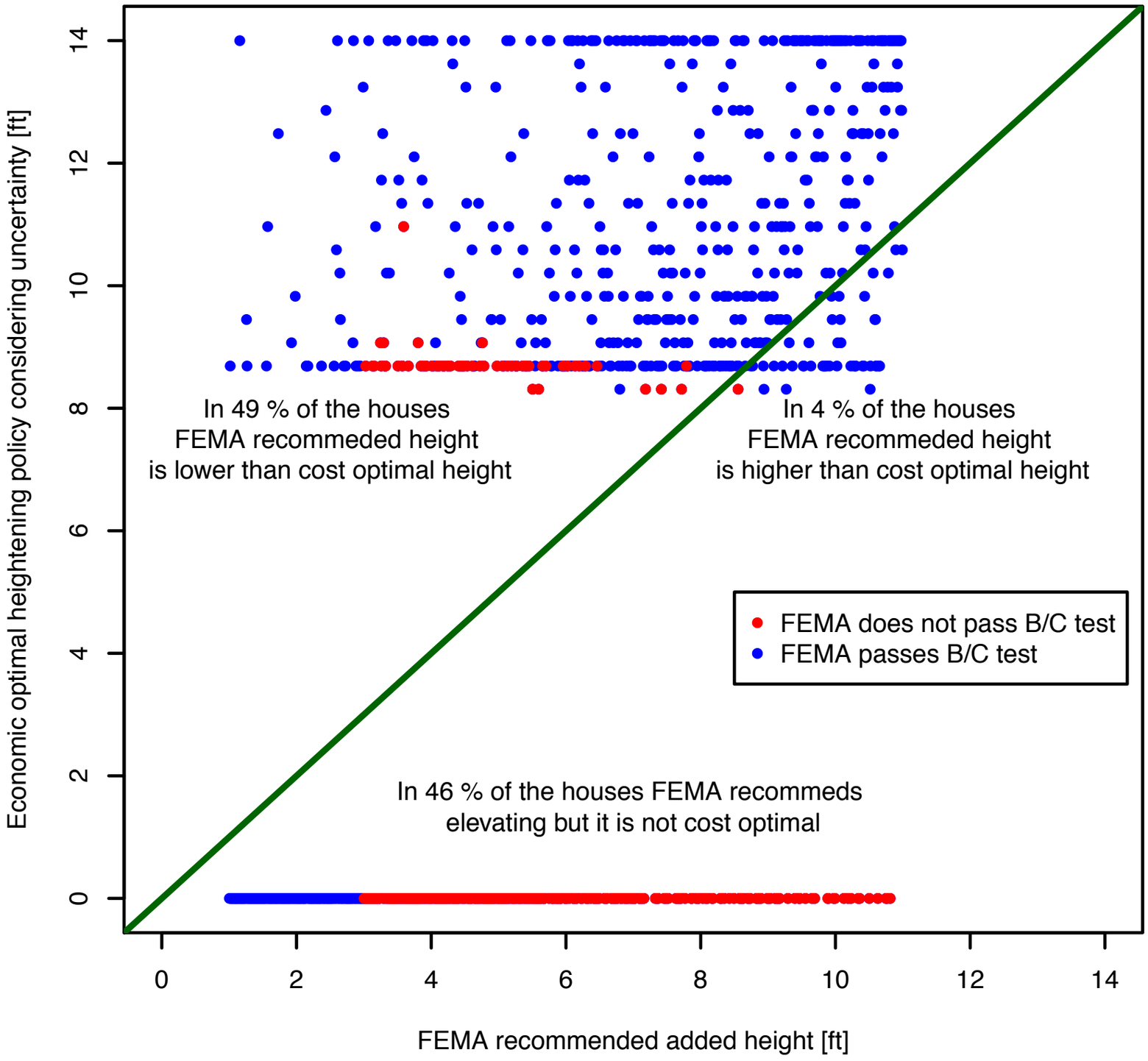




Analysis of objectives for a 4,684 square feet house with a value of 333,799 US$ that is -6.5 feet below the base flood elevation. The lifetime of this house is 45 years. a: Total cost, damages, and construction cost for various heightening scenarios. The hatched area indicates impractical heightening scenarios of less than 3 feet. The base flood elevation and FEMA's recommendation are shown via dotted blue lines. b: The b/c ratio for all heightening scenarios. c: safety for all scenarios. Please note that safety is defined as the probability of no floods during the house's lifespan.

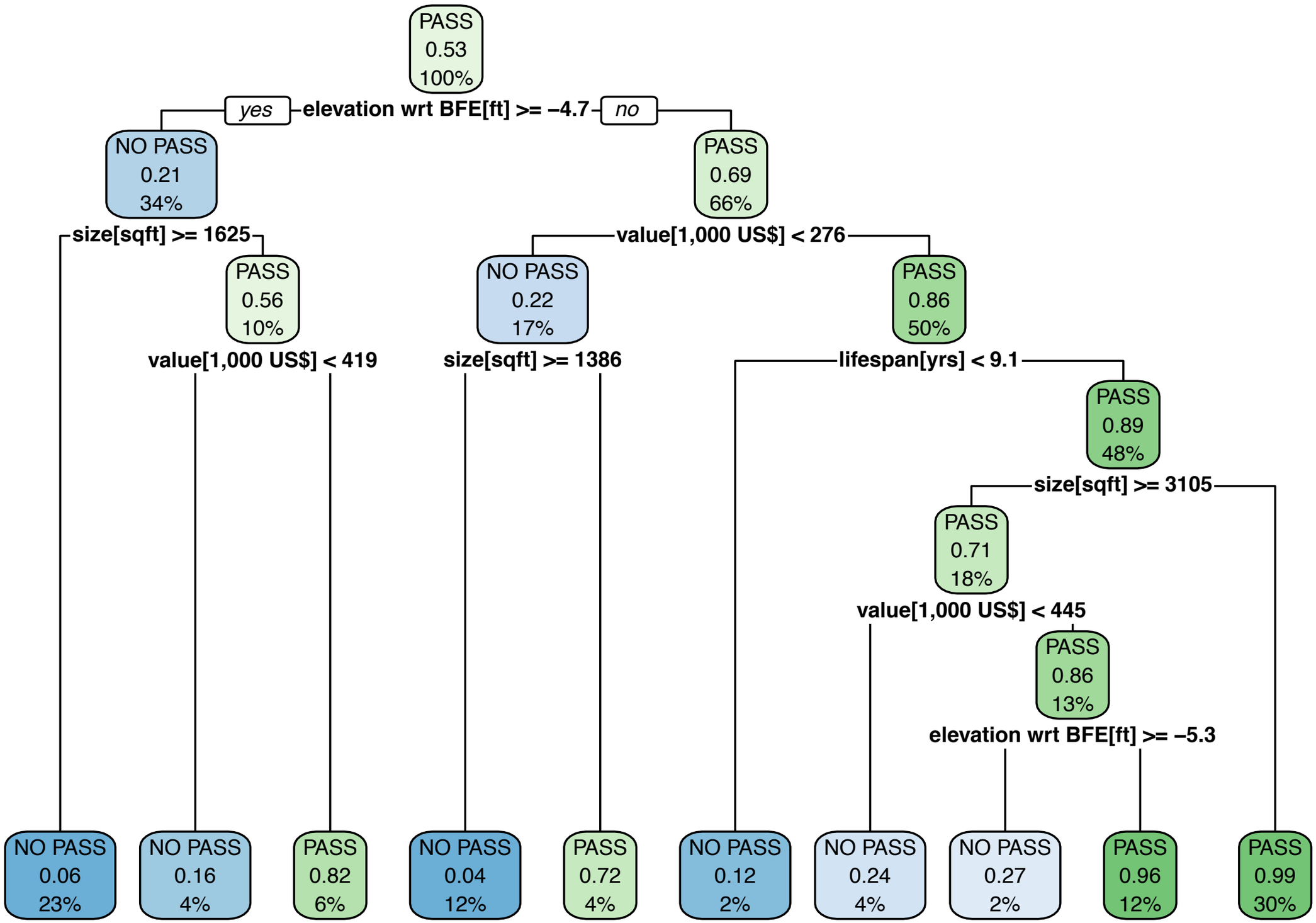
Cost of elevating this house to FEMA's recommendation is 1.18 times the current value of the house

Is FEMA's recommendation cost optimal? Is it cost effective?



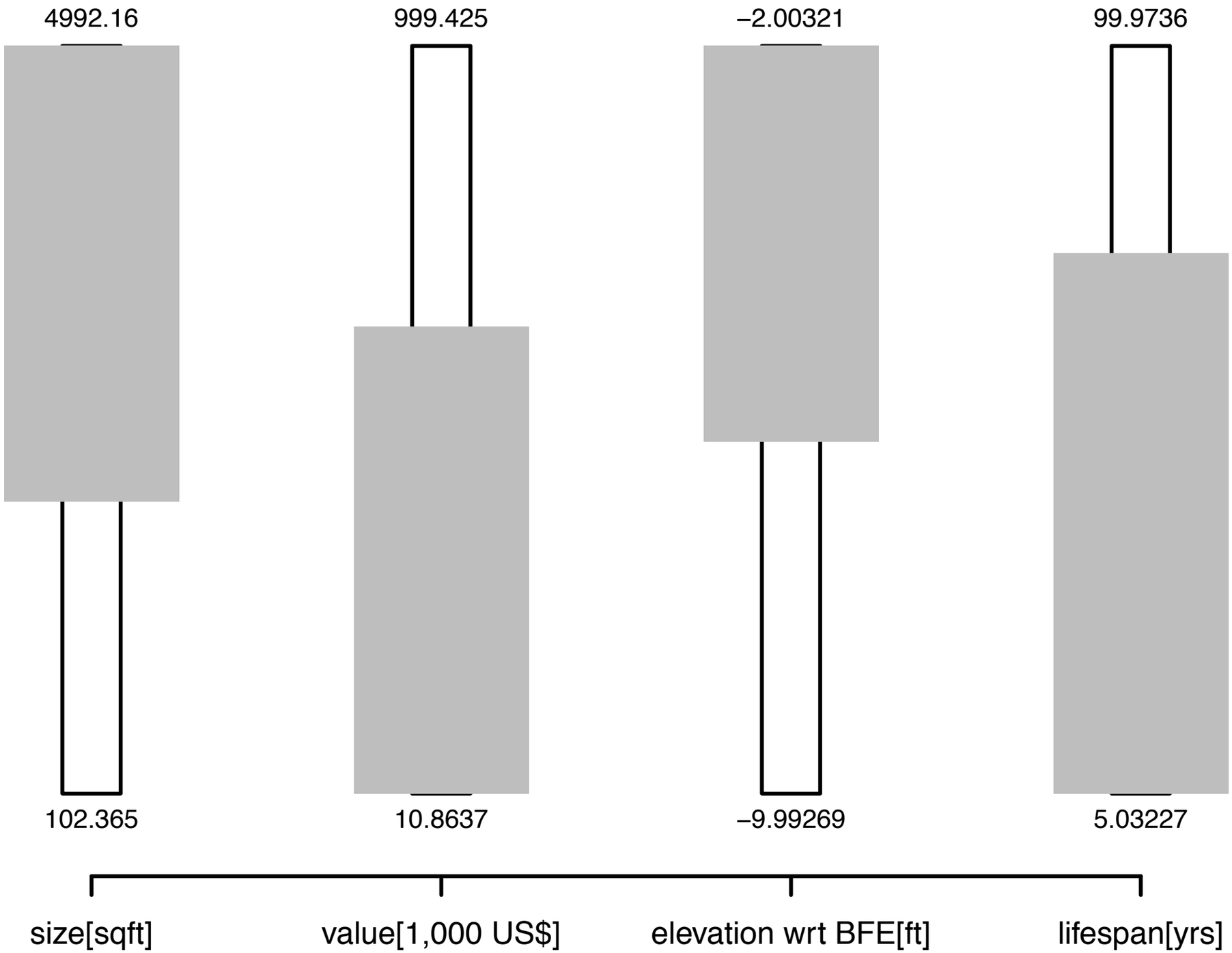
Scatter plot of FEMA recommended height versus the cost optimal height. Each point indicates a house in a range of hypothetical houses. For almost half of the houses, FEMA's recommendation is lower than the optimal elevation. In the half, elevating the house is not cost optimal at all while FEMA still recommends elevating them.

What house characteristics leads to sub-optimal performance of FEMA's recommendation?



The Classification and Regression Trees (CART) to indicate houses characteristics for which FEMA's recommendation either does not pass the cost-benefit test or has an upfront cost of higher than the initial house value.

What house characteristics leads to sub-optimal performance of FEMA's recommendation?



The Patient Rule Induction Method (PRIM) to identify house characteristics that result in sub-optimal performance of FEMA's recommendation. By sub-performance, we mean that the policy either does not pass the benefit-to-cost test or its upfront construction cost is higher than the initial house value.

SummaryFEMA's recommendation performance analysis

- Is FEMA's recommendation cost optimal?
    - In 8% of the sample, FEMA's recommendation is cost optimal.
    - In 49% of the Sample set, FEMA's recommended height is Lower than the optimal elevation.
    - In 46% of the sample set FEMA's recommends elevating a house while a cost-benefit analysis shows that walking away after the first major flood is a better policy than elevating the house.
- Is FEMA's recommendation cost effective?
    - In 65% of the sample set, FEMA's recommended policy passes the cost-benefit test but it does not pass the test in the remaining 35%.
    - The cost optimal elevation always passes the cost-benefit test.
- Does FEMA's recommendation an over-estimation or under-estimation?
    - Out of those houses where FEMA does not pass the cost-benefit test, in 85%, FEMA overestimates the height. In the remaining 15% it underestimates the height.
- What are the characteristics of houses where FEMA's recommendation is not cost optimal or cost effective
    - Expensive houses that are close to the base flood elevation should be raised more than FEMA's recommendation.
    - Big cheap houses that are close to the base flood elevation have high cost of elevating but low expected damages. These houses are not worth elevating and should be left as is.

Conclusions

- FEMA's recommendation is neither cost optimal nor cost effective. FEMA ignores that some houses are cheap and therefore their expected damages are low and these houses might not need to be elevated.

- Expensive houses should expect higher damages
- Larger houses are more expensive to elevate

- We offer a better decision criteria based on multiple objectives

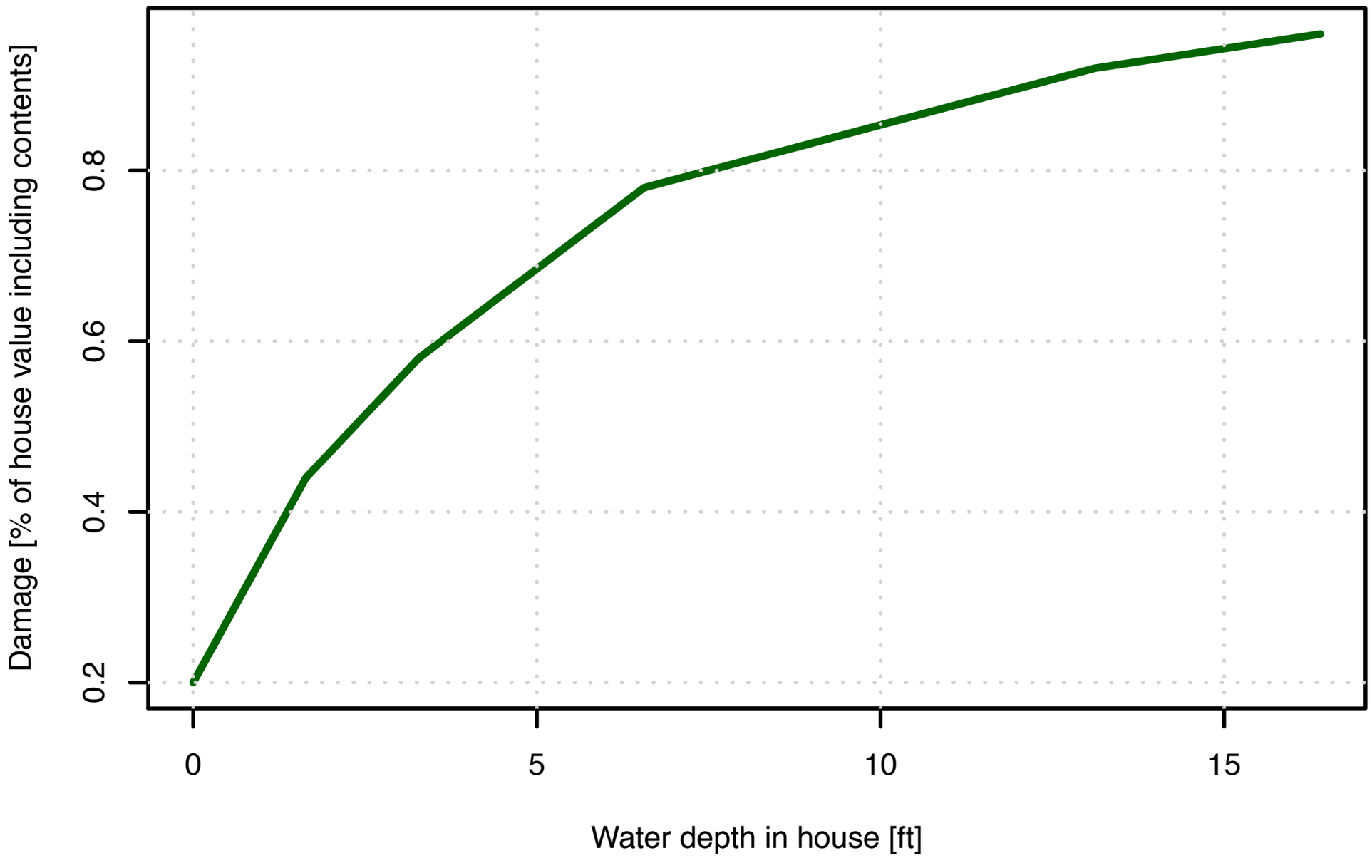
- Uncertainty is important: Considering uncertainty leads to a higher optimal elevation

- Considering uncertainty might change the final decision of raising a house or not. A decision that is cost optimal and cost effective ignoring uncertainty might flip when we consider uncertainty.

- Our recommendations for FEMA: House characteristics should be considered in this decision

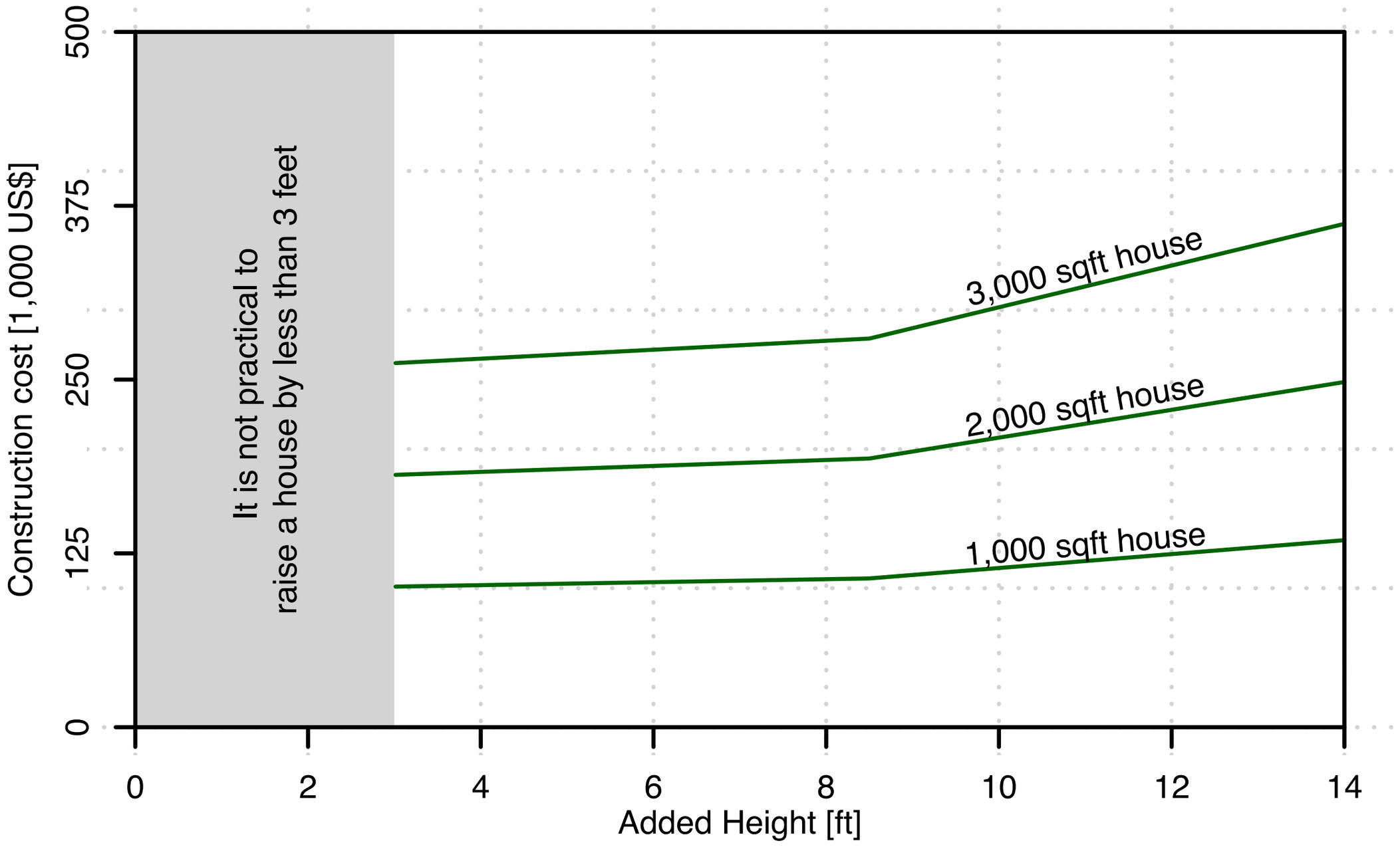
Supplementary materials

Depth-Damage function

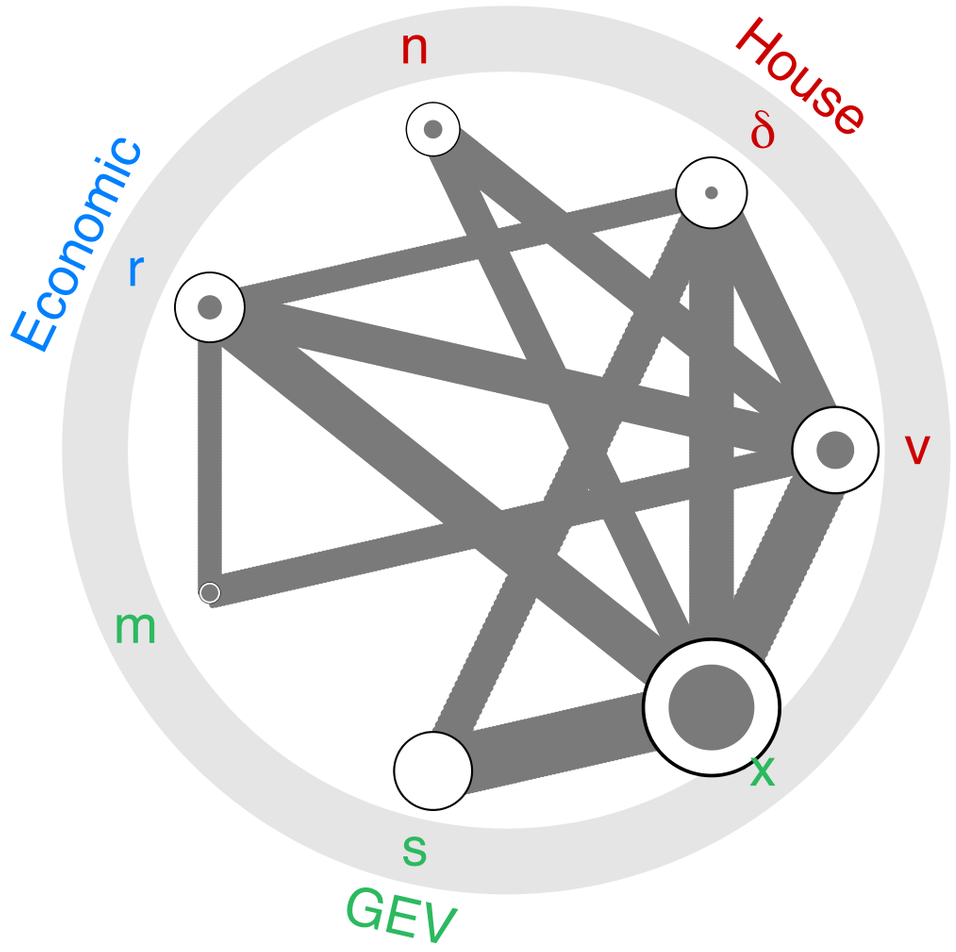


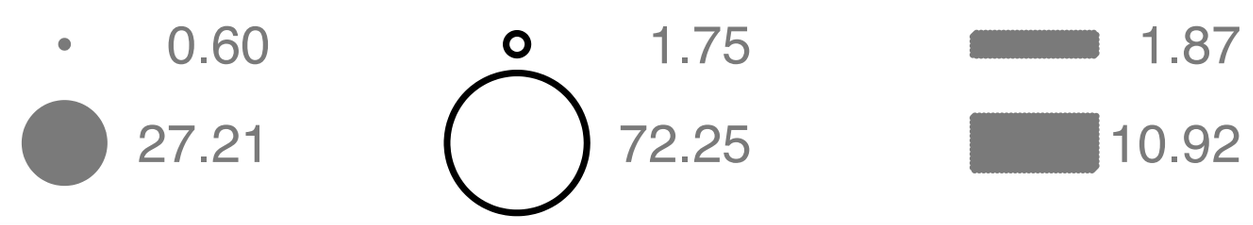
Depth-damage relationship adopted from EU report

Construction cost function



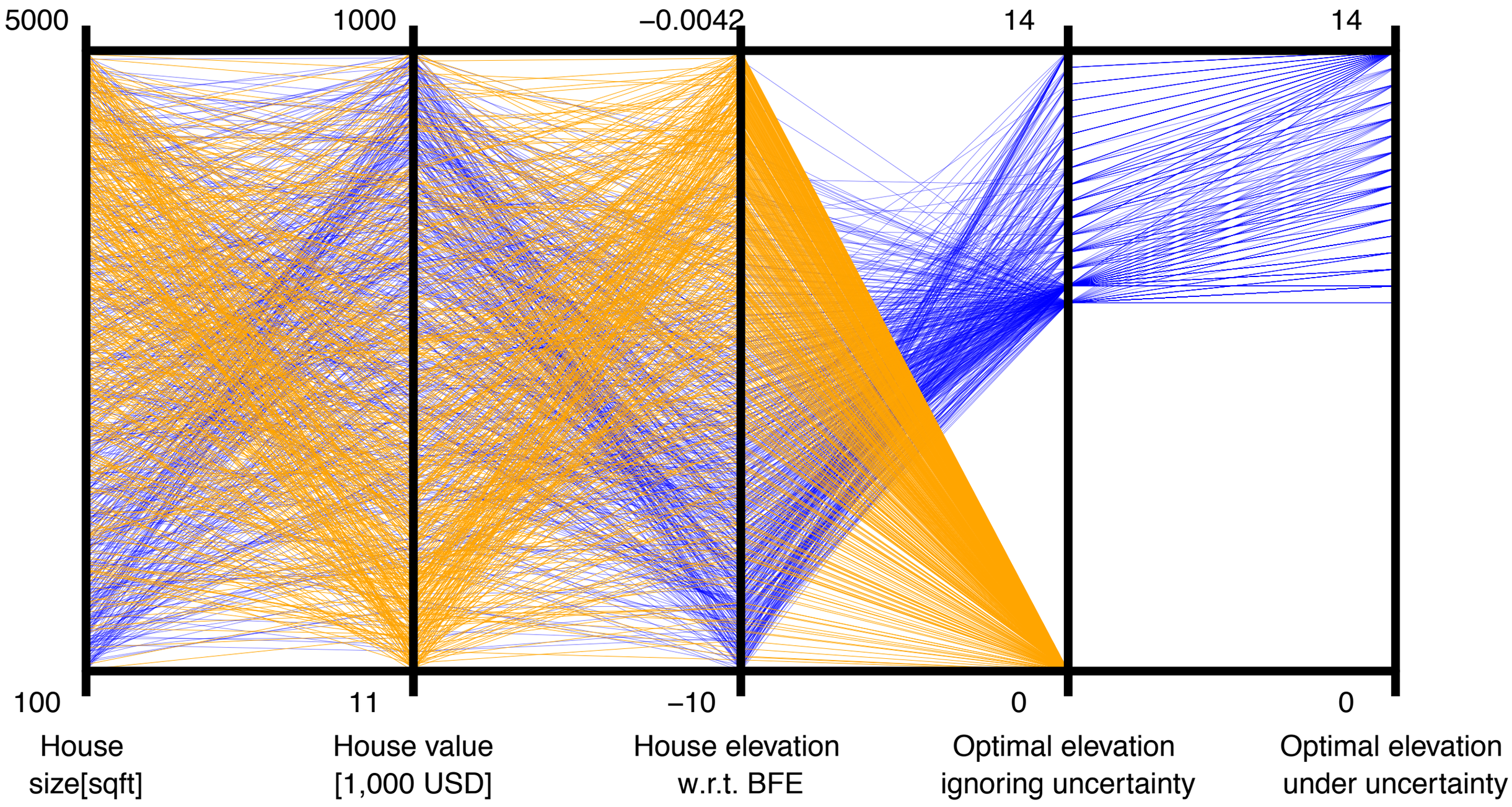
Construction cost for three sample houses with areas of 1,000, 2,000, and 3,000 square feet. The gray area indicates elevation of less than three feet which is not practical. This range is ignored in this study. The jump between 10 and 14 feet is because the method of raising a house becomes different and more expensive. These cost estimates are adopted from the CLARA model.


n
House
δ
Economic
r
v
m
x
s
GEV


0.60
1.75
1.87
27.21
72.25
10.92

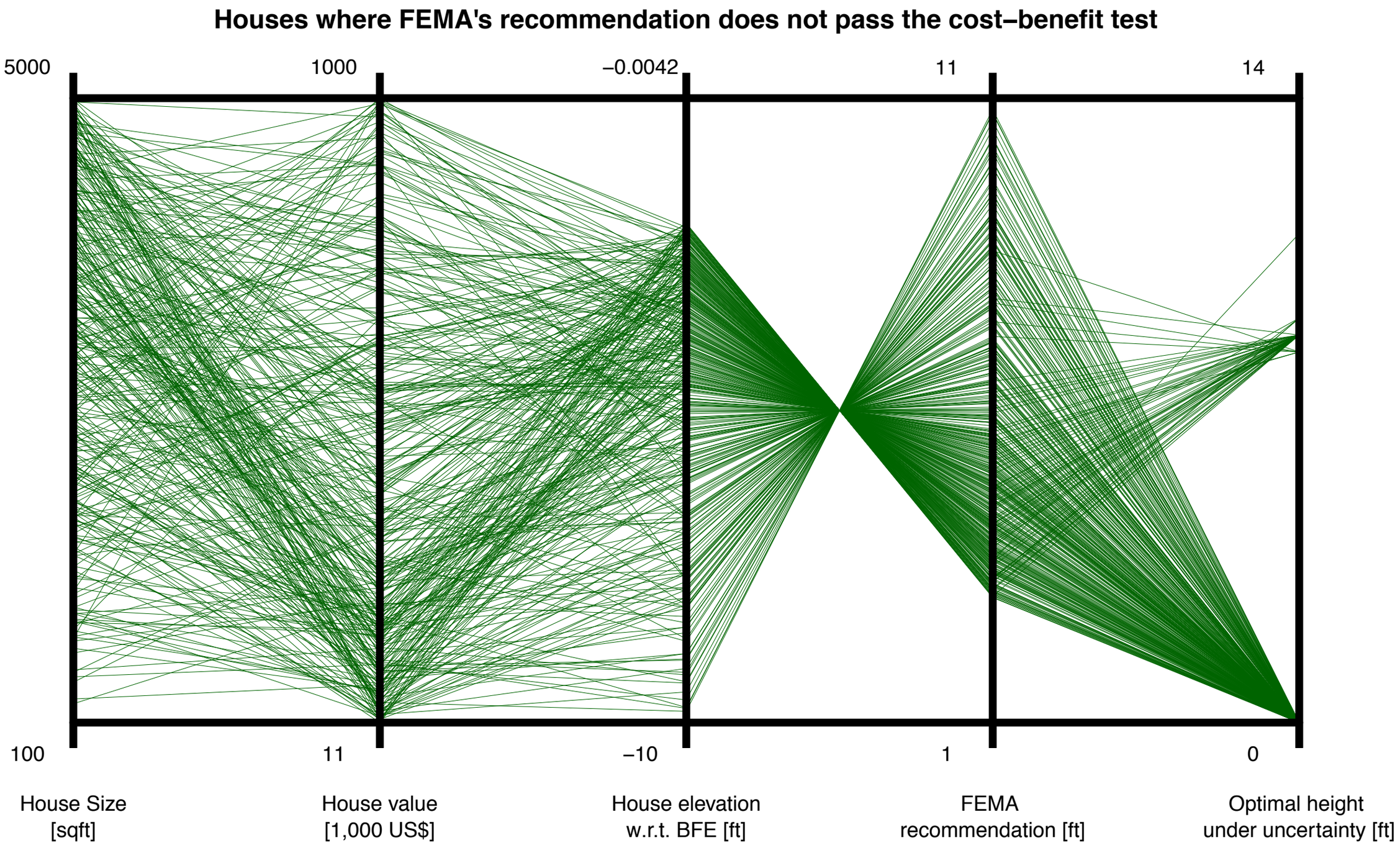
Old materials

What are the characteristics of the houses that should be elevated?
1. Elevating big cheap house whose lowest floor elevation is close to the BFE does not



Parallel axes plot for houses where both with-uncertainty and without uncertainty models agree that the house should be elevated (blue lines) or not (orange lines). Each line represents a house. Axes from left to right: House size, house total value including contents, house elevation with respect to the base flood elevation, optimal elevation in the model that ignores uncertainty and optimal elevation in the model that considers uncertainty.

What are those houses that FEMA does not pass the cost-benefit test?



Scatter plot of FEMA recommended height versus the cost optimal height. Each point indicates a sample house

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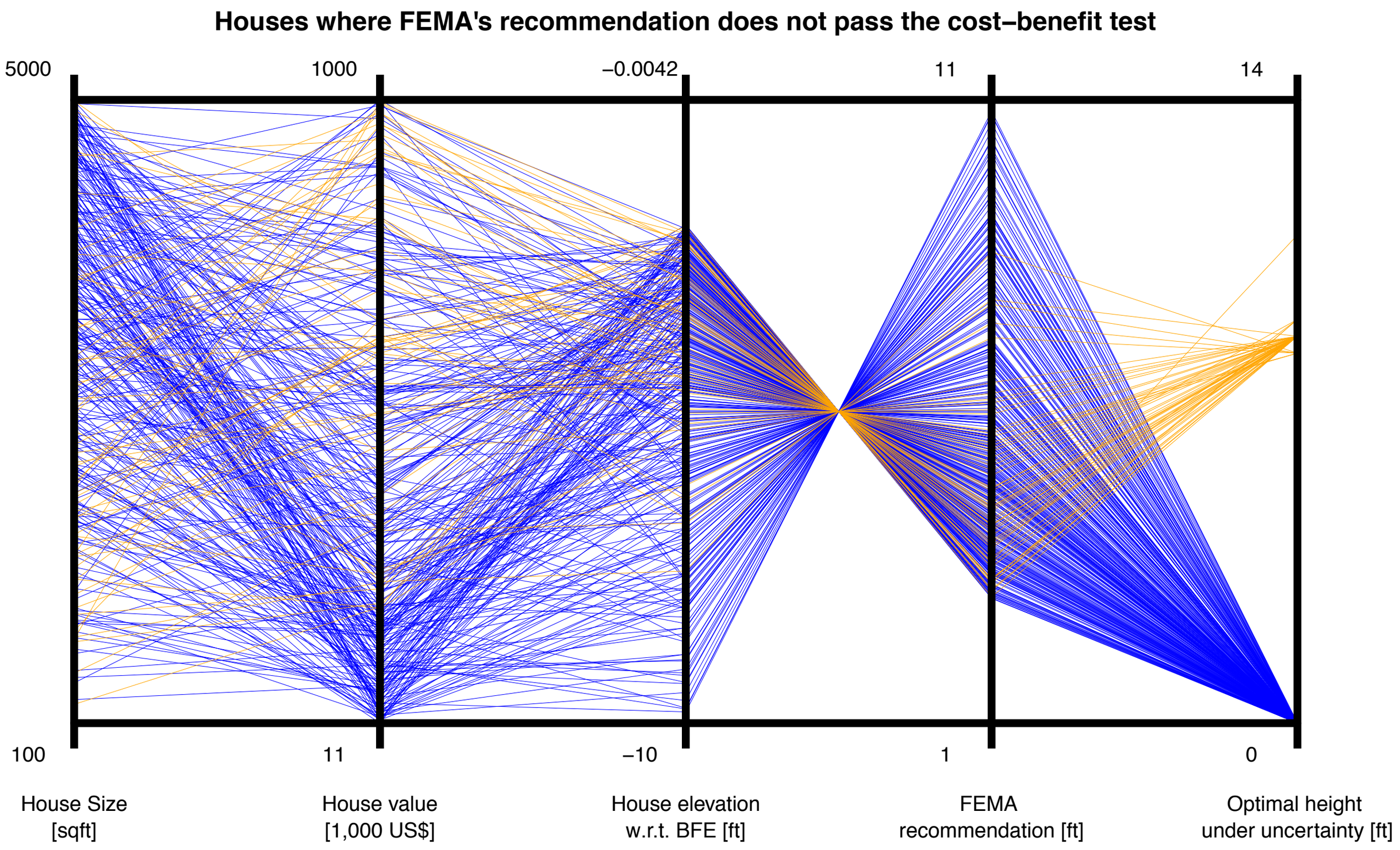

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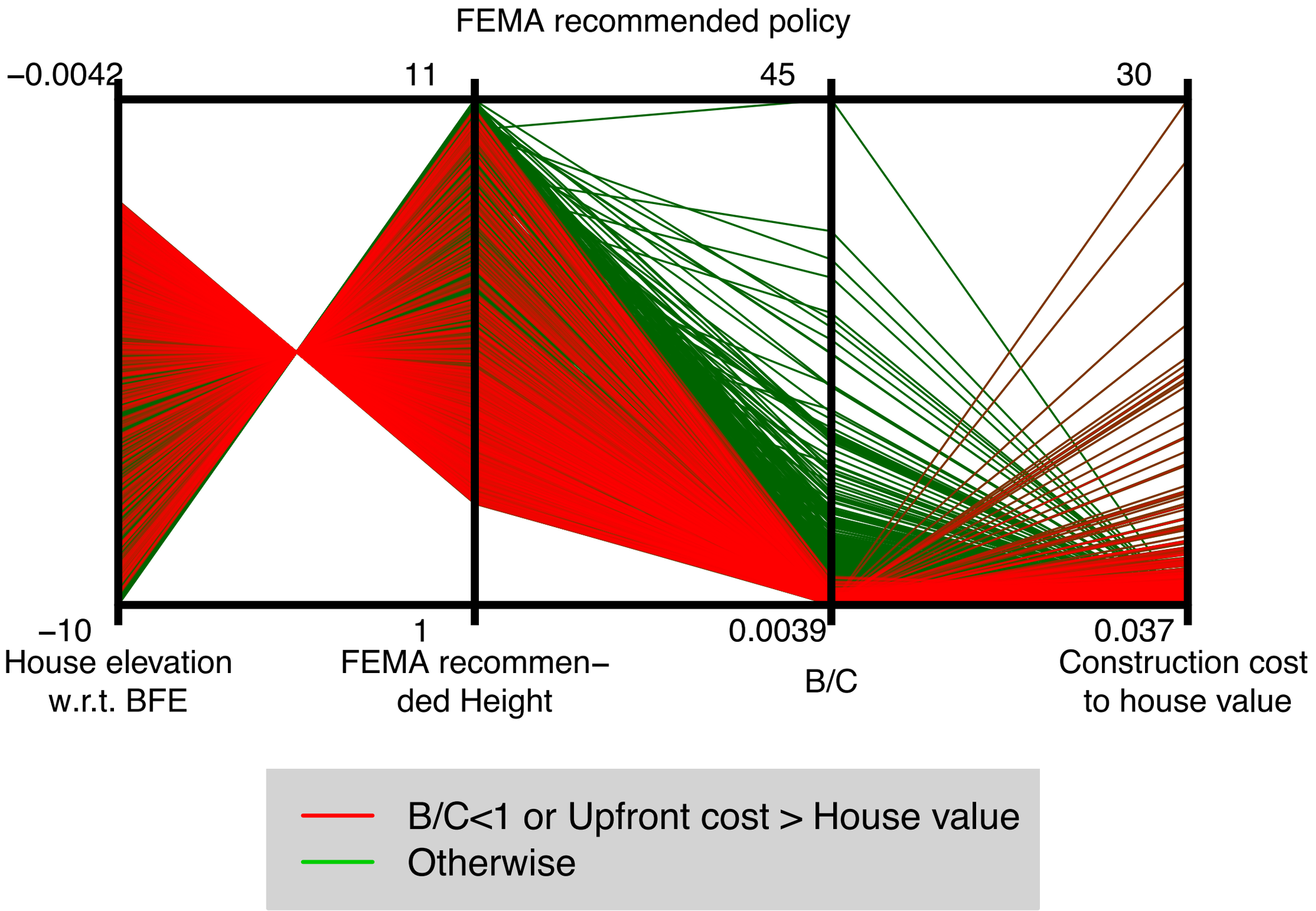
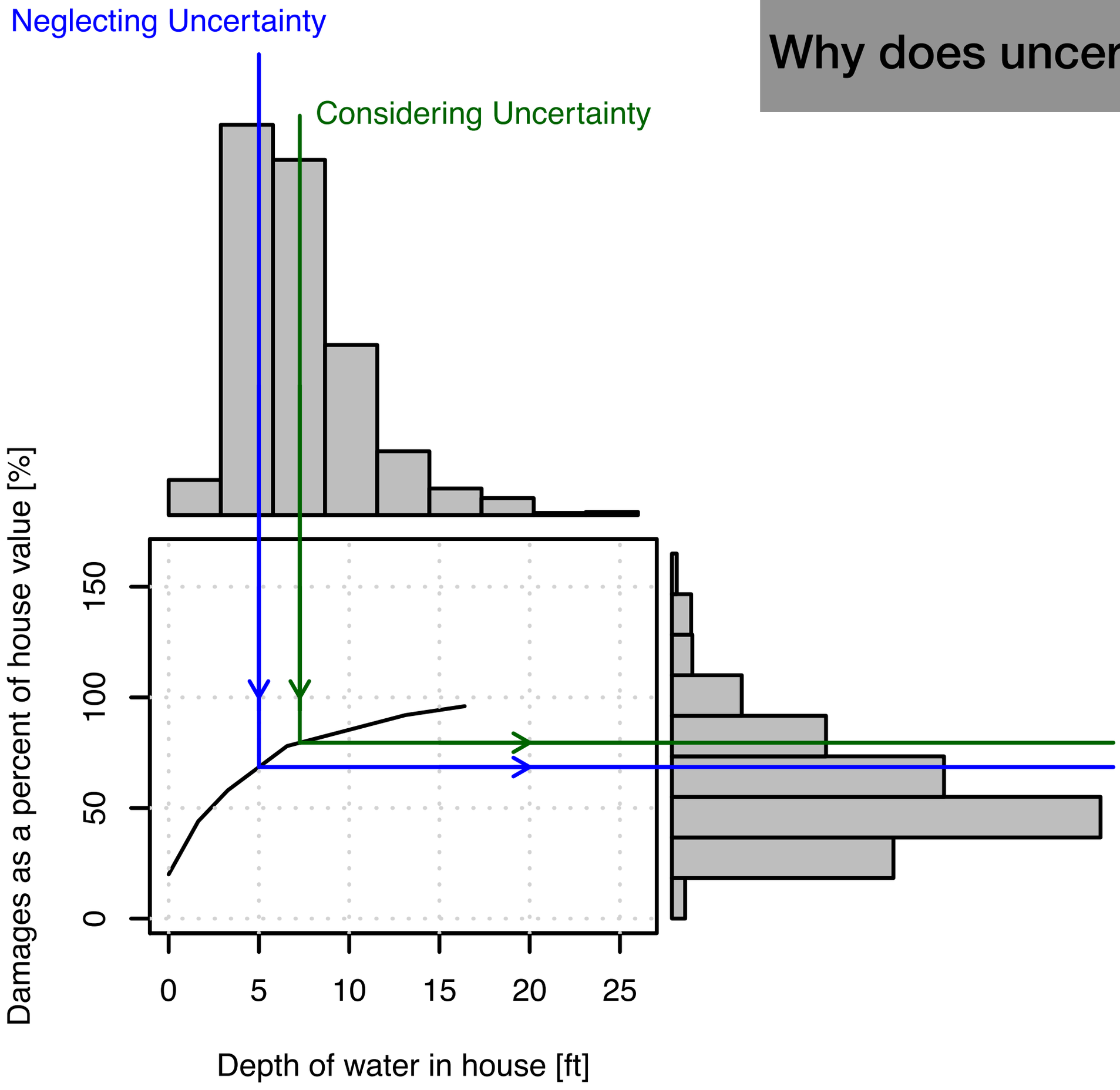
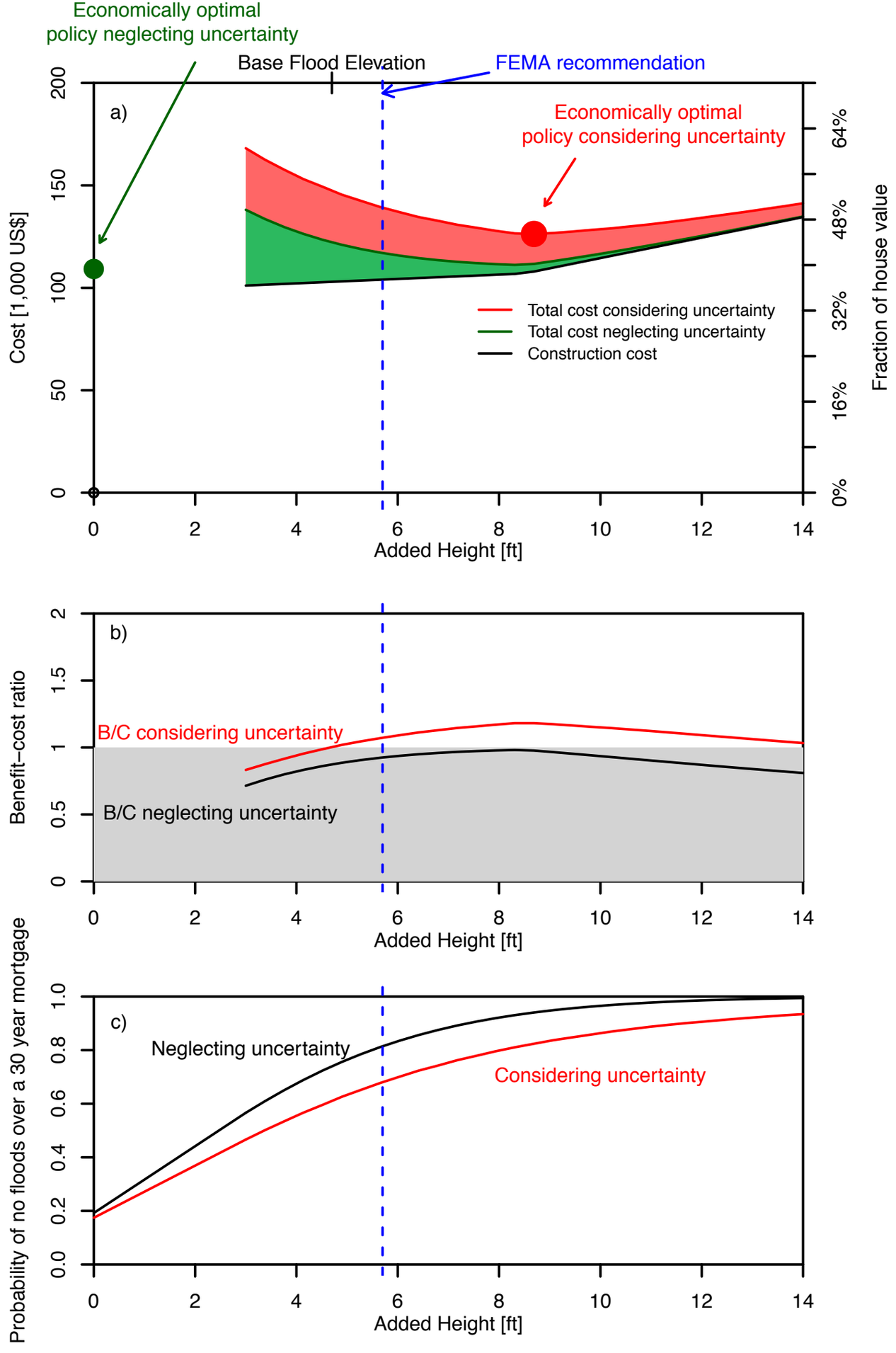


Parallel axes plot for FEMA recommendation. Axes from left to right: House elevation with respect to the base flood elevation, FEMA recommended added height, benefit to cost ratio, and the ratio of upfront construction cost to the house value. Each line represents a house in our sample set. Red lines indicate that either benefit-to-cost ratio is less than one or that the upfront cost for raising the house is so high that elevating does not make sense.

Why does uncertainty matter?




Economically optimal
policy neglecting uncertainty
Base Flood Elevation
FEMA recommendation
a)
Economically optimal
policy considering uncertainty
Total cost considering uncertainty
Total cost neglecting uncertainty
Construction cost
Cost [1,000 US$]
Fraction of house value
0
50
100
150
200
0%
16%
32%
48%
64%
0
2
4
6
8
10
12
14
Added Height [ft]
b)
B/C considering uncertainty
B/C neglecting uncertainty
Benefit–cost ratio
0
0.5
1
1.5
2
Added Height [ft]
c)
Neglecting uncertainty
Considering uncertainty
Probability of no floods over a 30 year mortgage
0.0
0.2
0.4
0.6
0.8
1.0
Added Height [ft]

Considering uncertainty results in higher expected damages