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Author(s):
Schmid, Franziska B.; Hersperger, Anna M.; Grêt-Regamey, Adrienne; Kienast, Felix

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Effects of different land-use planning instruments on urban shrub and tree canopy cover in Zurich, Switzerland

Franziska B. Schmid [a,b,*], Anna M. Hersperger [a], Adrienne Grêt-Regamey [b,c], Felix Kienast [a,b]

[a] Land Change Science, Swiss Federal Research Institute WSL, 8903 Birmensdorf, Switzerland
[b] Dept. of Environmental Systems Science D-USYS, ETH Zurich, 8092 Zurich, Switzerland
[c] Planning of Landscape and Urban Systems, Dept. of Civil, Environmental and Geomatic Engineering D-BAUG, ETH Zurich, 8093 Zurich, Switzerland

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ABSTRACT

Sustainable urban development requires not only dense and land-saving construction, but also a large share of urban vegetation. A planned unit development (PUD) is a land-use planning instrument that is often used to improve urban quality in urban renewal and densification worldwide. In this study, we analyse the influence of PUDs on urban vegetation in the Canton of Zurich, Switzerland, by contrasting them with conventional zoning. We modelled the share of shrub and tree canopy cover per neighbourhood block using generalized linear mixed effect models (GLMM), with the type of planning instrument as the focal predictor amongst other control variables known from the literature to be influential on urban vegetation. Results show that PUDs are associated with significantly less urban vegetation cover than conventional zoning. This is unexpected and raises concerns. Given how important PUDs are as levers for improving urban quality, their observed inability to promote valuable shrub and tree structures leads us to recommend that good landscape planning and long-term management of (existing and new) urban vegetation be included as an additional standard criterion of high priority in the assessment of future PUDs.

1. Introduction

While compact cities are promoted as a concept for spatial planning to combat urban sprawl and enhance economic growth (OECD, 2012), pressure is growing on urban green spaces (Haaland and Konijnendijk van den Bosch, 2015; Pauleit et al. 2005). Although the ecological, social and thus also economic value of the latter is becoming increasingly evident in the property development sector (Jerome et al. 2019; Sinnett et al. 2018), urbanization typically leads to reduced, fragmented and dispersed vegetation patterns (Dobbs et al. 2017). This is problematic, because particularly urban trees have been shown to have a significant impact on human well-being and health (Kardan et al. 2015), and to play an important role in regulating ecosystem services within the built environment (Grêt-Regamey et al. 2020). Paradoxically, ecosystem services in consolidating urban areas that experience infill development gain even higher social and economic importance as the number of local beneficiaries increases, and they thus reveal an even higher benefit (Gaffin et al. 2012; Gómez-Baggethun and Barton, 2013).

Good planning instruments are needed to optimize ecological, social and economic benefits of urban green spaces and vegetation in the process of urban densification (Fuller and Gaston, 2009), to make cities part of the solution to the problems they create (Elmqvist et al. 2019; Grimm et al. 2008). Particular attention should be paid to larger shrubs and trees: They have higher demands on their environment as lawns or meadows, e.g., regarding space and soil depth, and need much more time to develop. It is therefore of great concern, that tree cover in urban areas is globally decreasing (Nowak and Greenfield, 2020). So far, developers have had little-to-no incentives to preserve established urban vegetation (Brunner and Cozens, 2013), despite the availability of different planning instruments to control land-use and urban development. For example, tree ordinances are an instrument directly targeting the preservation of urban vegetation and were found to mitigate the negative effects of increasing densification on urban ecosystems (Hilbert et al. 2019; Landry and Pu, 2010). However, the use of these specific policies clearly varies between different municipalities and there appears to be a general lack of attention towards trees on private land (Conway and Urbani, 2007). Overall, the capacity to regulate for protection of urban trees in the private domain currently appears rather limited (Clark et al. 2020). On the other hand, the relation of larger urban vegetation with general land-use planning instruments has

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* Correspondence to: Swiss Federal Research Institute WSL, Zürcherstrasse 111, Birmensdorf 8903, Switzerland.
E-mail address: franziska.schmid@wsl.ch (F.B. Schmid).

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received little attention in research to date.

Conventional zoning, for example, can be viewed as one of the primary regulatory instruments of land-use planning (Kayden, 2020). Sometimes referred to as “Euclidean zoning”, it appeared about 100 hundred years ago, with the aim to avoid crowding of buildings and the creation of public health, safety, or fire hazards and to separate badly compatible land-uses (Elliott, 2008). It is used to regulate land-use type and activities, as well as maximum building height and density, which in turn influence diverse environmental processes (Wilson et al. 2003). Hill et al. count zoning ordinances among the most effective policies for the protection of tree canopy (2010). However, they also limit the possibilities of how buildings can be placed and thus how they define the remaining open space (Talen, 2013). When combined with minimum boundary distance regulations for shrubs and trees, this can result in sometimes very constrained potential space for new larger urban vegetation.

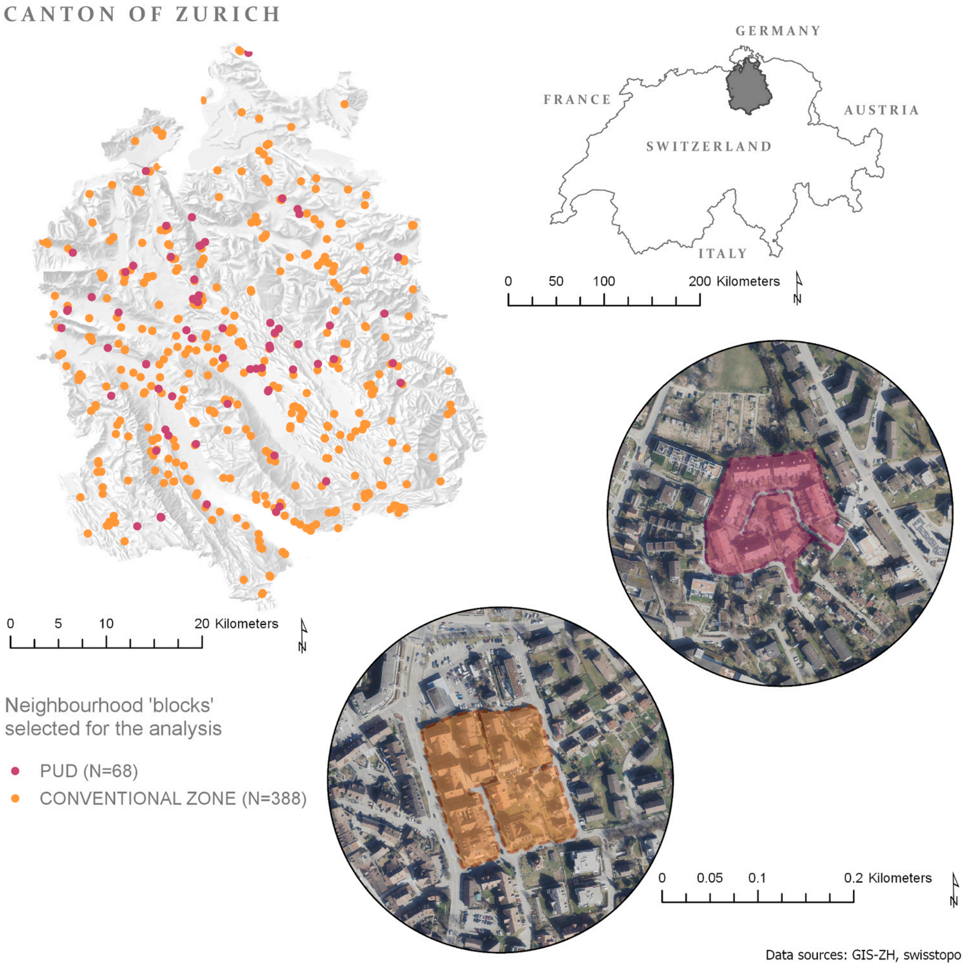
Planned Unit Developments (PUDs) are a more flexible alternative to rigid zoning regulations, as they permit deviation from the zoning code within locally defined areas, a concept which appeared approximately half a century later (Rohe, 2009). Ideally, PUDs lead to mutual benefits for both the developer and the municipality (Elliott, 2008): For example, they can be used as a tool to foster compact built-up development, environmental protection, open space dedication and the implementation of urban design principles (David, 2015). While there is increasing concern for building quality in the course of densification, PUDs are becoming more important as they offer municipalities better control of urban development (Gerber, 2016). Since urban vegetation is an essential element of high-quality developments and developers are required to comply with neighbourhood landscaping ordinances, we assume that residential or mixed-used areas (further) developed or transformed as projects under a PUD regime will have higher shares of shrub and tree cover than areas (further) developed under conventional zoning (cf. Lowry et al. 2012 and Hill et al. 2010). Yet, as David highlights, there is generally little empirical knowledge regarding the use and implementation of PUDs as planning instruments (2015).

Particularly, it is unclear to which extent PUDs might support larger urban vegetation structures, in comparison with conventional zoning. By their nature, PUDs cannot be evaluated for regulatory compliance with the zonal code, therefore, it is essential to assess how they serve public interest (David, 2022). One way to do so is to compare their characteristics with developments that have occurred under conventional zoning. In the present study, we address the question of whether residential or mixed-used areas (further) developed or transformed according to PUD regulations differ in shrub and tree canopy cover from such areas (further) developed according to conventional zoning regulations.

2. Methodology

2.1. Study area and unit of analysis

The Canton of Zurich (Fig. 1) is one of the most economically dynamic regions of Switzerland, with a high standard of living and a growing population. Besides the population, the built-up area per capita



Data sources: GIS-ZH, swisstopo

Fig. 1. The study area Canton of Zurich, Switzerland with the selected neighbourhood ‘blocks’ (unit of analysis) for residential and mixed uses, including exemplary aerial views.

has increased over a long period of time and, only in recent years has a slight decline in this ratio been observed, indicating a densification in the use of urbanised land (Hofer, 2020). Apart from conventional zoning, other planning tools have been used to support urban renewal and the transformation of brownfield sites during the past decades. An important instrument in this context is the *Gestaltungsplan* (Cathomas and Hersperger, 2018), which is what we refer to in this article as a PUD. The instrument was legally introduced in our study region in 1975, at that time aiming mainly for good urban planning solutions in the vicinity of nature and cultural heritage sites, highly frequented public transportation hubs or high emission facilities (Bösch, 1987). It can be applied in a specific area to enable deviations from provisions on standard construction practices and from cantonal minimum distances. Concurrently, it must determine the number, location, and external dimensions of buildings, as well as their use and purpose, with a reasonable margin of discretion but in a binding manner. It can include specifications regarding the design of the surrounding area (Canton of Zurich, 1975). The aim is to achieve high-quality developments in terms of urban planning, architecture and settlement (Bühlmann, 2021).

The units of analysis in our study are neighbourhood 'blocks', defined as a contiguous group of parcels that share the designation to the same land-use zone (or PUD) and which are delineated by other physical separating elements such as roads, rivers, etc. (Canton of Zurich, Statistical Office).

2.2. Data

2.2.1. Dependent variables

We were particularly interested in the proportional cover of neighbourhood blocks with higher vegetation structures, such as shrubs and trees. We used a raster dataset with a resolution of 0.5 m, containing vegetation heights, which had been previously derived from public light detection and ranging (LIDAR) data (Federal Office of Topography swisstopo, 2017). The raster data were reclassified into shrub cover (1–4 m) and tree canopy cover (>4 m). Subsequently, two ratios were calculated by dividing the area of each vegetation category by the total block area. Statistical modelling was then performed on the two ratios 'shrub area per block area' and 'tree area per block area' as dependent variables.

2.2.2. Focal predictor

To distinguish between conventional zones and PUDs, our main independent variable, we used the data of the Swiss Cadastre of Public Law Restrictions on Landownership (PLR Cadastre, Canton of Zurich, 2022). This has been established in recent years with the aim to provide simplified access to the most important public law restrictions on landownership, corresponding to the land register for information relating to private law restrictions (Geodesy and Federal Directorate of Cadastral Surveying). Data on land-use planning can be divided into area-wide zones for 'basic land-uses' (*Grundnutzungen*) and 'overlaying land-uses' (*überlagernde Nutzungen*), registered by overlying polygons, lines, or points. The perimeters of PUDs are registered as overlying polygons.

2.2.3. Other potential predictors

A wide variety of other factors that correlate with urban vegetation cover have been identified in the literature. For example, housing density and the process of densification has been reported to negatively affect the amount of urban vegetation (e.g. Daniel et al. 2016; Lee et al. 2017). Luck et al. detected a quadratic relationship, with mid-range values of density providing highest vegetation cover (2009). Housing typology also plays a role, as single-family, detached homes are positively related to tree stewardship (Troy et al. 2007). A positive relationship between parcel size and tree cover has been reported by Bigsby et al. (2014), however, other studies did not find such evidence (Conway and Urbani, 2007). Urban vegetation is related to land-use type and mix (Bigsby et al. 2014; Lowry et al. 2012; Wilson et al. 2003), depending on the scale of analysis (Mincey et al. 2013). A special case is the variable housing age or time since urban development. It has been shown to be positively associated with urban vegetation cover, however, sometimes a quadratic relationship has been reported, as well as interaction with other independent variables (Bigsby et al. 2014; Daniel et al. 2016; Grove et al. 2006; Kendal et al. 2012; Landry and Chakraborty, 2009; Lowry et al. 2012; Pham et al. 2017; Troy et al. 2007). Conflicting results have been reported regarding the relationship of population density with urban vegetation (Bigsby et al. 2014; Dobbs et al. 2017; Hilbert et al. 2019; Kendal et al. 2012; Troy et al. 2007).

Our aim was to select those potential predictors of urban vegetation in which PUDs are very likely to differ from conventional zones, to control for these confounding variables in our models. For example, since PUDs are a more recent planning tool than conventional zoning and are often used to increase built-up density, we control for housing age as well as housing and population density (Table 1). Moreover, we assume that in our case PUDs are used mainly for the development of multi-family homes, whereas single-family homes are largely found within conventional zones. We thus included housing typology in our analysis. Furthermore, PUDs are less restricted by the structure of parcels and instead of parcel size, we used the size of block area, as defined in Section 2.1. Additionally, we included as categorical variable the type of land-use zone, as PUDs are often developed in town centres and designed to accommodate mixed uses or, for example, with the purpose to preserve or carefully develop building ensembles that are part of the townscape heritage. We also expected to see differences in the implementation of PUDs across different planning authorities and therefore added municipalities as a random effect variable. Table 1 gives an overview of all the predictors included in our analysis.

2.3. Analysis

Pre-processing of the spatial data was conducted in Python 3.6.6 and ArcGIS Pro 2.3.0, as shown in Fig. 2. The vegetation height data were reclassified according to the two abovementioned vegetation categories (green boxes). The data on PUDs were combined with an existing cantonal dataset containing conventional zones, statistical census and registry data at the level of neighbourhood blocks (our units of analysis; blue boxes). The volume of each building was derived in two steps: first, we subtracted the digital terrain model (DTM) from the digital surface model (DSM) of the Canton of Zurich from 2017; second, we multiplied the mean height difference per building with the area of the respective building footprint (grey boxes). All input data were combined at block level and blocks filtered according to the following criteria (yellow boxes): Only areas for residential and mixed-uses (including town centres and townscape heritage) were selected and blocks were included only in the analysis if they contained at least some built-up volume, if the median year of construction was 1990 or later, and the newest building constructed before the year 2000. These criteria ensured that we reached a balanced sample with regard to neighbourhood age and that the vegetation, which was planted during or directly after the last construction phase, had two to three decades to grow, to account for time-lag (cf. Luck et al. 2009). Furthermore, in the case of PUDs the newest building had to be constructed after the year of approval (to exclude any PUDs which might not have been implemented yet). Finally, conventional zones were only selected, if the block area was at least as big as the smallest included PUD, but not bigger than the largest one and if the built-up volume was at least as much as the smallest built-up volume within the selected group of PUDs.

Statistical analysis was performed using R version 4.2.3 (R Core Team, 2023). We established the significance level at $\alpha = 0.05$ throughout all tests. We first applied descriptive statistics to analyse the structure of predictor variables, assessed the variables for potential multicollinearity and selected the candidate set of predictors to be included into the modelling process. When selecting a suitable statistical

Table 1

Potential predictors for shrub and tree canopy cover included in the analysis apart from focal predictor ‘planning instrument’.

Potential predictors	Related references	Description of data[1]		Total (N=456)			Conventional zones (N=388)			PUDs (N=68)		
		Unit of analysis	Source[2]	Min	Median	Max	Min	Median	Max	Min	Median	Max
Area size	Bigsby et al. 2014	Neighbourhood block area size (m^2)	Neighbourhood statistics	460	4892	20422	465	4924	20337	460	4182	20422
Housing density	Daniel et al. 2016 Lee et al. 2017 Luck et al. 2009	Built-up area per total block area	Digital Surface Model (DSM) + Digital Terrain Model (DTM) + Cadastral survey data	0.01	0.22	0.84	0.03	0.23	0.84	0.01	0.14	0.77
		Built-up volume per block area		0.11	1.87	16.61	0.25	1.89	16.61	0.11	1.39	10.92
Housing typology	Troy et al. 2007	Share of single-family homes	Neighbourhood statistics	0	0.25	1	0	0.29	1	0	0.14	1
		Share of multi-family homes		0	0.42	1	0	0.33	1	0	0.53	1
Housing age	Bigsby et al. 2014 Daniel et al. 2016 Grove et al. 2006 Kendal et al. 2012 Landry and Chakraborty, 2009 Lowry et al. 2012 Luck et al. 2009 Pham et al. 2017 Troy et al. 2007	Median year of construction	Cadastral survey data with building age	1990	1995	1999	1990	1995	1999	1990	1995	1999
Population density	Dobbs et al. 2017 Kendal et al. 2012 Troy et al. 2007	Inhabitants per ha of block area	Neighbourhood statistics	0	77	449	0	72	449	0	84	329
		Employees per ha of block area		0	5	1317	0	5	1317	0	9	682
Type of land-use zone	Bigsby et al. 2014 Lowry et al. 2012 Wilson et al. 2003	Residential	Neighbourhood statistics (PLR Cadastre)	Count:	239		Count:	205		Count:	34	
		Mixed-uses			90			79			11	
		Town centre			17			15			2	
		Townscape heritage			110			89			21	
Administrative unit	Threlfall et al. 2022	Municipalities (N=162)	Neighbourhood statistics									

[1]) Descriptive statistics of the input data after pre-processing and selection of cases (Fig. 2).

[2]) All datasets were obtained via the Geographic Information System of the Canton of Zurich (GIS-ZH, available online at https://maps.zh.ch/).

model, two main characteristics of our data had to be considered:

1) We had a hierarchical data structure as our observations (neighbourhood blocks) are nested within municipalities. We expected this administrative unit to influence how planning instruments are implemented according to different governance practices (Threlfall et al. 2022). Thus, zoning data are not truly independent: every municipality has its own legislative and executive body and its own zoning ordinance, which means that zones of the same type within a municipality are more like each other than they are like zones of the same type within different municipalities. However, zones of the same type in different municipalities may be more similar to each other than they are to zones of different types within the same municipality. Therefore we decided to include both variables ‘municipality’ and ‘type of zone’ as crossed random effects to our model and estimated an ‘unconditional random intercept model’ for each of them to test whether the variables showed a clustering effect (Garson, 2021). All other predictors from Table 1 were considered as potential fixed effects.

2) The two dependent variables did not meet the criteria for linear regression: they represent proportion data (coverage of total block area with shrub / tree canopy cover) and their characteristic of being bounded at 0 and 1 suggests non-normally distributed errors around a fitted relationship (Buckley, 2015). We therefore decided to apply a generalised linear mixed model (GLMM), which combines the advantages of linear mixed models and generalised linear models (Bolker et al. 2009). We used the R package *glmmTMB* because of its high flexibility (Brooks et al. 2017). This allowed us to use a ‘logit’ link function with a Beta error distribution, as suggested for modelling percent cover data (Buckley, 2015).

The interpretation of GLMM is not trivial. Bolker et al. discuss three general types of inference: frequentist hypothesis testing, model selection and Bayesian methods (2009). We chose hypothesis testing and model selection using an information theoretic approach. This means that we assessed the contribution of each fixed effect by comparing the fit for the full model (including all fixed and random effects) and several nested models, in each of which a single factor was excluded (cf. Bolker et al. 2009). For the pairwise comparisons, we used a likelihood ratio test. Since this model selection procedure is not without controversy (ibid.), we additionally ranked the models using the Akaike information criterion (AIC).

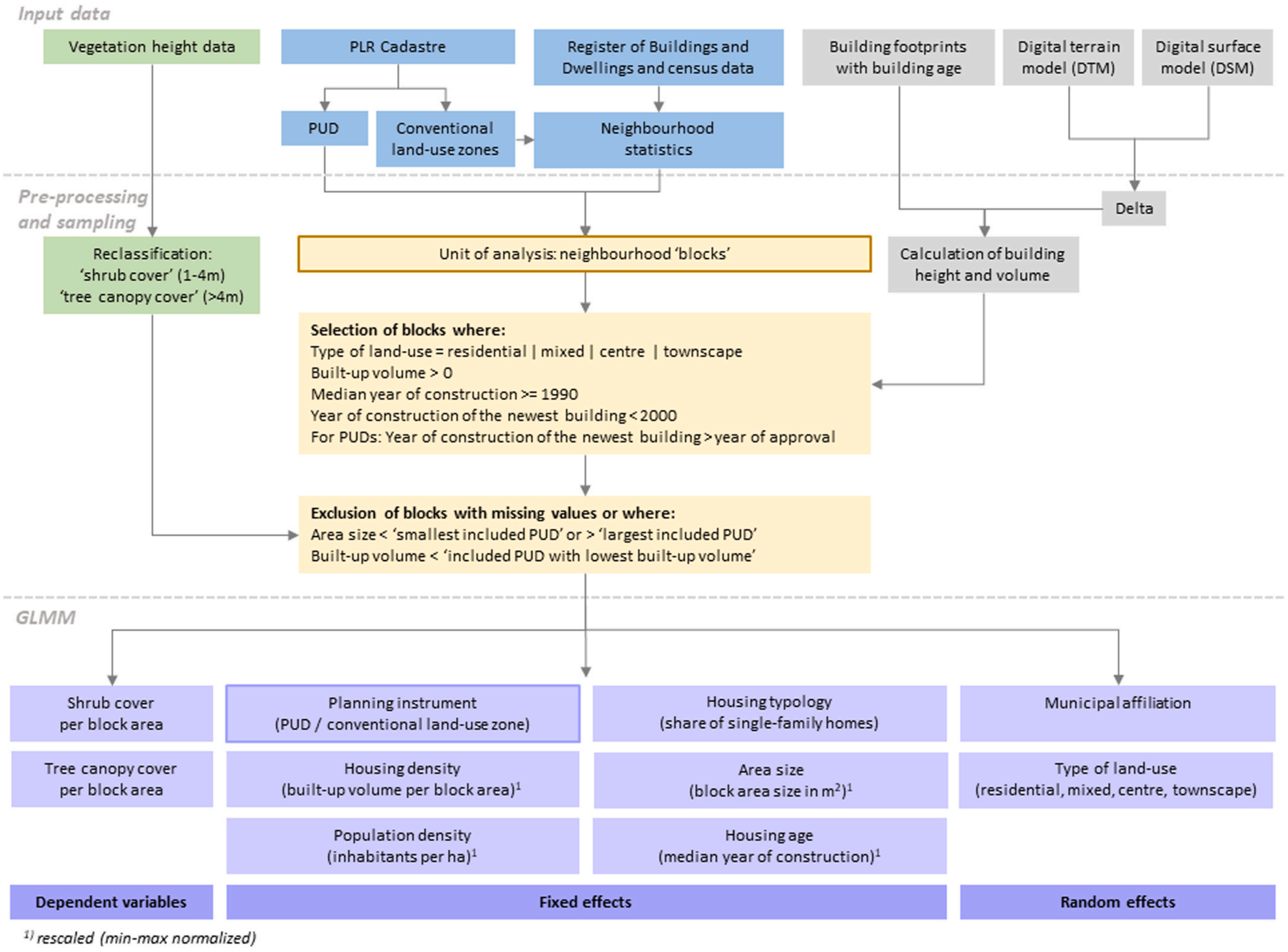


Fig. 2. Schematic representation of the study design: input data and pre-processing of dependent variables (green boxes) and predictors (planning and statistical data: blue boxes; housing data: grey boxes), selection of cases (yellow boxes) and statistical modelling (purple boxes).

3. Results

3.1. Candidate set of predictors

When simply comparing the distribution of shrub and tree canopy cover per type of planning instrument, a clear difference was noticeable; conventional zones appeared to be 'greener' than PUDs (Fig. 3). This raised the question, whether this is the result of one or more confounding variables or not.

Prior to estimating the models, the initial set of numerical variables was checked for multicollinearity. Using hierarchical clustering, we determined groups of variables with a Pearson correlation coefficient higher than 0.6 (Fig. 4). We selected one variable per cluster, which led us to the following candidate set of numerical predictors: housing density (built-up volume per block area), population density (inhabitants per ha), proportion of single-family homes, block area size (m^2) and housing age (median year of construction). Together with our focal variable (planning instrument), these predictors were included as fixed effects in the subsequent analysis. Numerical variables were rescaled (min-max normalized) before modelling. The categorical variables 'municipality' and 'type of land-use' were included as random effects.

We further investigated whether the chosen numerical control

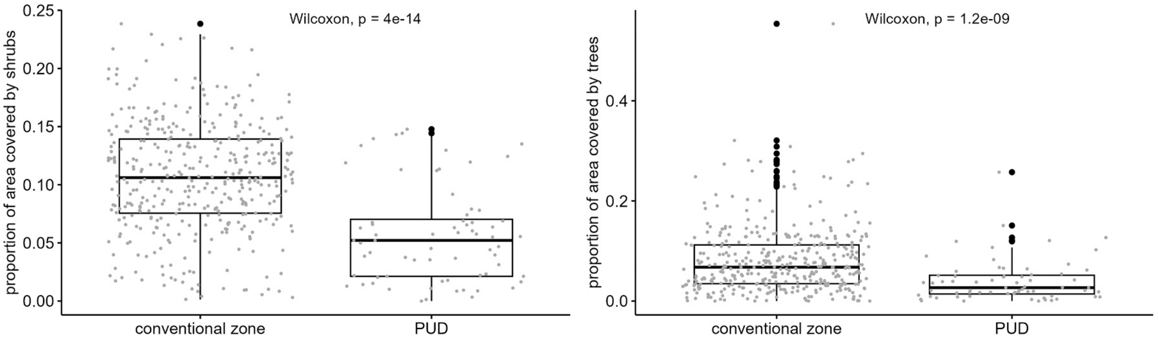


Fig. 3. Comparison of urban vegetation within the two different types of planning instruments.

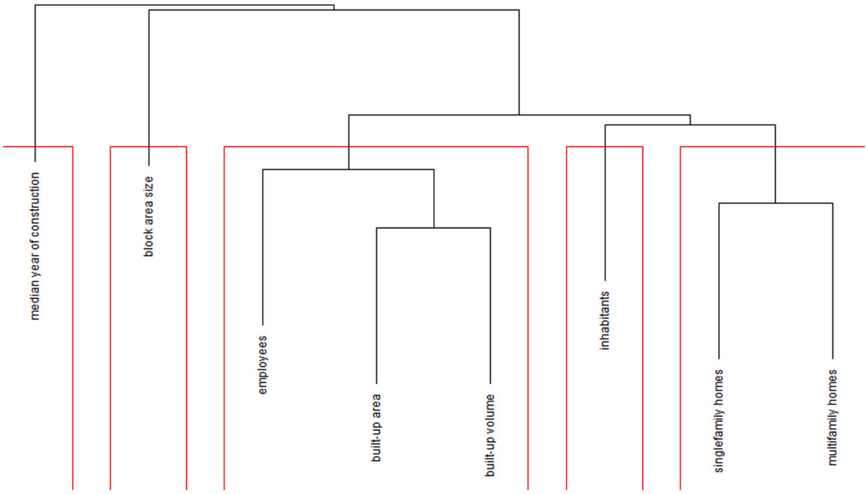


Fig. 4. Hierarchical clustering of the correlation structure among potential numerical predictors for urban shrub and tree canopy cover, displaying groups of variables with a Pearson correlation coefficient higher than 0.6.

variables showed similar distributions for PUDs as for conventional zones (Fig. 5). As the data are non-normally distributed, we conducted Wilcoxon rank-sum tests, which revealed a significant difference regarding the two types of planning instruments solely for the predictor ‘built-up volume per block area’. Surprisingly, the median is higher for the conventional zones, than for the PUDs. In contrast, particularly the variables ‘block area size’ and ‘median year of construction’ are well balanced for the two groups, as intended by our sampling strategy.

3.2. *Modelling results*

The ‘unconditional random intercept models’ (each with one random effect only, excluding any fixed effects) revealed a variation in urban shrub and tree canopy cover across municipalities and land-use types. The clustering effects are significant at $\alpha = 0.05$ with all p values clearly below, and thus support the use of multilevel models in both cases. Furthermore, both the information theoretic ranking (AIC) and the pairwise comparisons (likelihood ratio test) of each of the full models with their nested models indicated that our focal predictor ‘planning instrument’ was a significant predictor for both shrub and tree canopy cover per block area. Contrary to our initial expectations, but confirming the first impression perceived from the boxplots in Fig. 3, conventional zones significantly lead to higher proportions of both categories of vegetation than PUDs. Other statistically significant predictors for shrub cover were ‘housing density’, ‘population density’ and ‘housing typology’. In contrast for tree canopy cover, the two variables ‘area size’, and ‘housing typology’ had a significant effect. (Table 2)

4. Discussion and conclusion

4.1. *Less shrub and tree canopy cover in PUDs*

Our research indicates that in the Canton of Zurich, PUDs generally led to less shrub and tree canopy cover than conventional zoning in areas that have been (further) developed around two to three decades ago. It could be argued that this is not surprising, as PUDs generally allow for higher built-up density than surrounding neighbourhoods. In (further) developing and transition areas, where PUDs are typically implemented,

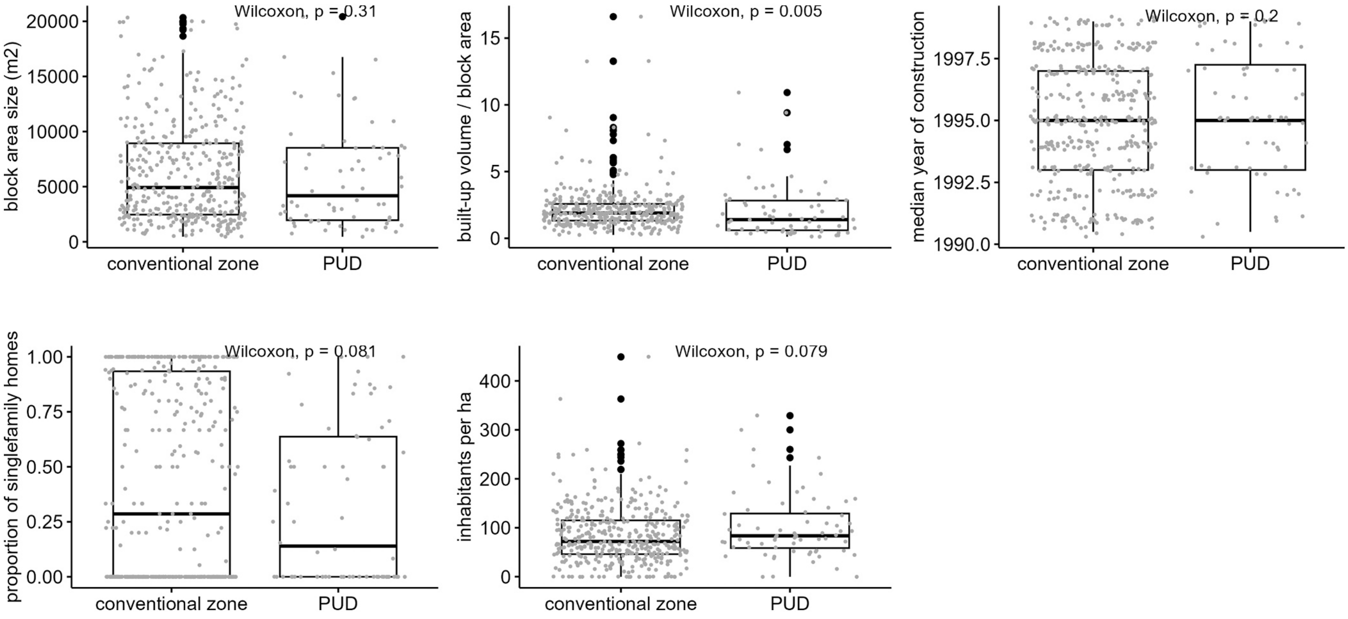


Fig. 5. Boxplots of control variables for the two types of planning instruments (focal predictor).

Table 2

Comparison of the reduced, nested models, in each of which one predictor of the full model is omitted ('predictor of interest'): a) results of the information theoretic ranking of the reduced models; b) results of the likelihood ratio tests for the pairwise comparisons between the full model and the reduced models; c) direction of influence of the predictor of interest, derived from its coefficient in the full model.

	Predictor of interest → (omitted)	**Planning instrument** (PUD)	**Area size** (block area size in m^2)^1	**Housing density** (built-up volume per block area)^1	**Housing age** (median year of construction)^1	**Population density** (inhabitants per ha)^1	**Housing typology** (proportion of single-family homes)
	Dependent variable: shrub cover per block area						
a	**AIC (Δ)**	101.7	1.1	12.1	-2	28.5	31.9
b	**χ2**	103.79	3.2203	14.22	0.0877	30.538	34.026
	p-value	< 2.2e-16 ***	0.07273	0.0001626 ***	0.7671	3.273e-08 ***	5.438e-09 ***
c	**Direction of influence**	-	-	-	-	+	+
	Dependent variable: tree canopy cover per block area						
a	**AIC (Δ)**	30.8	5.4	-1.7	1.4	-1.6	7.8
b	**χ2**	32.899	7.5411	0.4084	3.5485	0.4794	9.9338
	p-value	9.706e-09 ***	0.006031 **	0.5228	0.0596	0.4887	0.001623 **
c	**Direction of influence**	-	+	+	-	-	-

^{1}) rescaled (min-max normalized)

building footprints increase while trees and shrubs compete with other needs for the limited outdoor space (Daniel et al. 2016). However, Lowry et al. hypothesized that PUDs are favourable to a more rapid infill of urban trees, where developers are required to follow neighbourhood landscaping ordinances (2012). Further Hill et al. identified high quality smart growth projects as one of the more effective policies in protecting tree canopy cover (2010). Still, even when controlling for the variable 'built-up volume per block area' and other variables (block area size, housing typology, housing age, population density), we found a clear negative and statistically significant contribution of PUDs to the proportion of shrub and tree canopy cover per block area. Our results suggest that this planning instrument could not mitigate the conflict of objectives between urban densification and the preservation of urban vegetation in the past, but rather resolved it to the detriment of vegetation.

One possible explanation could be that higher urban vegetation structures have played a subordinate role in the development management frameworks of the municipalities under study. While urban green is an omnipresent aspect in today's planning discussions, other aspects of design quality might have been more explicitly checked during the assessment of PUDs. It is possible that the design principles applied simply do not support a higher amount of urban vegetation in comparison with conventional zoning (cf. Conway, 2009). For example, the construction of large underground parking limits the root space for large trees. There also appears to be variation between municipalities, which concurs with Threlfall et al., who analysed individual and structural drivers of density and diversity of street trees and found variation across municipal authorities (2022).

It could also be argued that the observed negative impact of PUDs on urban green may be a case of poor implementation of planning contents (cf. Wilson et al. 2003), or that developers may have been reluctant to plan for large tree and shrub cover within PUDs for economic reasons. Pandit et al. (2013) reported that property values decrease when trees are located on the property itself or on adjacent private property, but increase with tree canopy cover on adjacent public space. Pragmatic and political limitations might hinder the ability of PUDs to meet the vision of their early advocates (Whittemore, 2015). Here, we touch on how planning is affecting urban land change, which is a very complex system of interactions (cf. Hersperger et al. 2019). Our findings could be linked to other work that has shown that the Swiss planning system is not in favour of contiguous redevelopments (Götze and Jehling, 2022).

4.2. Limitations of the study and directions for future research

Our dependent variables reflect only one, rather limited dimension of urban green. We deliberately excluded any lawns or meadows and focused on larger shrubs and trees as important carriers of cultural and ecosystem services, which are particularly vulnerable in densifying urban environments. However, we looked at them only in terms of their general abundance. To ensure sustainable compact urban development in the long term, urban vegetation is vital not only in quantity but also in quality of composition and structure (Threlfall et al. 2016). For example, the cooling effect can vary between different tree species (Bowler et al. 2010). Moreover, green spaces in general should be adapted to the needs of the population (Badiu et al. 2016), but this requires detailed knowledge about how to best link demand and supply of cultural ecosystem services (Hegetschweiler et al. 2017).

Our study analysed developments constructed at least 20 years ago. This approach was necessary to adequately account for the time needed for the establishment of shrub and tree vegetation but may limit the relevance of the results to contemporary practice. Planning evaluation studies are routinely faced with this type of time lag when assessing planning outcomes (He et al. 2022).

Furthermore, the present study did not account for any potential private-law contracts (cf. Gerber, 2016) or measures capturing added value, for example, to support the establishment or enhancement of urban vegetation and public green spaces. Such compensation measures could possibly manifest themselves outside of the actual project perimeter of PUDs and thus would not be linked to the planning instrument in the data we have at hand.

The model evaluation methods we used, inform us about the relative importance of each variable, compared to the other predictors within a model. They do not provide, however, a measure of the overall performance of the model, i.e., we do not know how much variance is explained by the model (R^2). This means, that the relevance of the results strongly depends on the quality of the initial selection of predictors used for modelling, i.e., whether the most important predictors have been included. Else it could be possible, that even the relatively most important predictor in the model is still practically irrelevant.

Based on our literature review, we assume, that we were able to include most of the important predictors characterising the physical environment, however, we did not include any socio-economic factors (except indirectly with the 'proportion of single-family homes'). Mixed findings have been reported from different regions regarding the influence of social-stratification and lifestyle variables, such as household income (Daniel et al. 2016; Gerrish and Watkins, 2018; Landry and Chakraborty, 2009; Lowry et al. 2012; Padullés Cubino and Retana, 2023; Pham et al. 2017; Schwarz et al. 2015; Threlfall et al. 2022), educational level of the inhabitants (Daniel et al. 2016; Kendal et al. 2012; Lowry et al. 2012; Luck et al. 2009; Pham et al. 2017; Threlfall et al. 2022), proportion of ethnic/racial groups (Landry and Chakraborty, 2009; Lowry et al. 2012; Luck et al. 2009; Schwarz et al. 2015), proportion of owner-occupied housing (Landry and Chakraborty, 2009), average household size and median population age (Lowry et al. 2012), and lifestyle behaviour (Grove et al. 2006; Troy et al. 2007). Generally, income seems to be an important, positive predictor for urban tree canopy cover in regions with high economic inequality, whereas educational level appears to be more relevant for regions with less economic disparity (Kendal et al. 2012). Additionally, biophysical conditions play a role particularly in understanding variation in urban forest cover for different regions around the globe (Conway and Urbani, 2007; Nowak and Greenfield, 2020) and might also explain certain geographic variation in study results regarding some of the above socio-economic predictors (Bigsby et al. 2014). In the Swiss context, the relation between the distribution of urban vegetation and socio-economic factors and the question of equity have received so far rather little, but increasing attention (e.g. Guinaudeau et al. 2023; Pidoux and Guilbert, 2023). It is, however, unclear, for example, if wealthier neighbourhoods might tend to be greener because either, their residents can afford the space and maintenance of larger urban vegetation or are politically more influential regarding design and management of public green spaces close by. As we cannot rule out, that there are socio-economic differences between the populations living in PUDs and living in conventional zones, our current modelling results must be regarded with caution and further research is needed.

4.3. Conclusion and implications for planning practice

Much detail is needed in the design and implementation of planning instruments to preserve and enhance urban vegetation. Special attention should be paid to existing larger shrubs and mature trees, for example, with a reduction of (underground) car parking accompanied by alternative mobility strategies (Erlwein and Pauleit, 2021). PUDs can address such issues and should be used more consistently. Landscape planning and the long-term management of urban vegetation (existing and new) should thus be included as a high-priority standard criterion in the assessment of future PUDs and the treatment of large trees during and after the construction phase could be part of the construction permit procedure (cf. Daniel et al. 2016). In line with David (2022), the results of our study underline the importance of a good strategy to foster urban vegetation, particularly in the course of PUD developments. Design principles for green infrastructures, as proposed by Jerome et al. (2019), could offer guidance in the evaluation of PUDs. If the preservation and enhancement of urban vegetation is promoted as a fundamental aspect of good quality of life and as part of a desirable lifestyle (cf. Troy et al. 2007), rather than simply as a procedural requirement for developers, it could help to convey a positive picture that supports also successful urban growth management, adding to a more positive narrative (cf. Siedentop et al. 2022).

Moreover, if PUDs are used as a tool to mitigate negative social effects of urban densification, for example, as a lever to integrate social housing into market-rate development to counteract gentrification, they could improve both affordability and ecological equity of housing. However, both aspects need to be much more prioritised already in the planning process of PUDs. This is especially critical as long as conventional zoning, does not offer any means to mitigate the negative effects of widespread upzoning when aiming to foster urban densification (cf. Whittemore, 2021).

CRediT authorship contribution statement

Franziska B. Schmid: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Anna M. Hersperger:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Adrienne Grêt-Regamey**: Supervision, Writing – review & editing. **Felix Kienast:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DeepL in order to improve language and style of the article. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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