Impacts of Informal Trails in Forested Areas close to Zuerich

With special regards to mountain biking

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Abstract

Recreational use of forest areas results in some degree of environmental damage. This can include the formation of visitor-created informal trails. Nowadays, informal trail proliferation is an important management concern in many natural areas worldwide. To date, there is a lack in research focussing on mapping and investigating informal trail related impacts. These impacts can be severe, often resulting in resource degradation and habitat fragmentation.

This thesis examines informal trails within three peri-urban forested study areas close to Zuerich, Switzerland. It assesses the spatial distribution and characteristics of informal trail segments, as well as their contribution to trail-based fragmentation. Furthermore, the study examines to which extent off-trail mountain biking and associated unauthorized trail technical features impact these forested areas. Differences between informal trail segments used exclusively by mountain bikers and other informal trail segments are assessed. Data was collected during a two-month assessment period in early summer 2015. Informal trail segments were mapped using a GPS device.

Within the three study areas a total of 19.7km of informal trails was mapped. 76.9% of those trails were used by hikers and 71.2% were used by mountain bikers. More than one fifth of the total disturbed ground was associated with mountain biking on informal trails. Unauthorized trail technical features accounted for less than 10% of the impact caused by off-trail mountain biking. The present study found that informal trail segments used exclusively by mountain bikers and those used by other user groups can differ in their characteristics, in their spatial distribution and in the degree of fragmentation they cause. However, research findings showed significant higher values in average slope, side-effect of trail width and maximum trail incision for informal trail segments used exclusively by mountain bikers.

Results highlight how informal trail use can result in cumulative damage to forested areas close to urban settlements. Additionally, findings show how informal trails can fragment forested areas internally. Results of this study can provide a scientific basis for management decisions to minimize the impacts caused by informal trails. Management should seek to limit the formation of informal trails and should close inappropriate ones, which pose a threat to the ecosystem.

Keywords: informal trails, landscape fragmentation, forests, mountain biking, trail impacts, trail technical features

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1. Introduction

1.1 Context

Forests provide diverse and extraordinary settings for recreational users. In times of rapid urbanization globally, they are important places for outdoor recreation within and adjacent to urban areas (Heer et al., 2003). Since recreational use in natural areas is on the rise, forest remnants serve as hotspots for outdoor activities in urban regions (Ballantyne et al., 2014a; Ballantyne et al., 2014b). Higher income and greater time availability have contributed to the diversification and variety of activities carried out in natural settings, such as hiking, horse-riding and biking (Heer et al., 2003). Despite being a beneficial site for recreational activities, including health, education and well-being benefits, recreational areas close to urban regions are often subjected to human-related impacts (Ballantyne et al., 2014b; White et al., 2006). Recreational use and accompanied infrastructure can result in negative changes to the environment and are widely acknowledged to pose a threat to the integrity of the ecosystems in which they are carried out (Ballantyne et al., 2014b; Pickering, 2010).

Trails are a core infrastructural component of providing access to natural areas and play a substantial role in managing visitor traffic (Marion & Leung, 2001; Wimpey & Marion, 2011a). Well-designed and managed trail systems facilitate access for visitors to various points of interest and provide a unique recreational experience (Wimpey & Marion, 2011a). In contrast, inadequately designed, constructed and managed trails can contribute to resource degradation (Hill & Pickering, 2006; Marion & Leung, 2011). Trail-based recreation can impact the environment, including trail widening, damage of vegetation and composition change, soil compaction and erosion. Further impacts are for example changes in trail surfaces, root exposure, introduction and spread of invasive species, wildlife disturbance and the proliferation of informal trails (Marion & Leung, 2004; Pickering et al., 2010a).

Even though, formal and informal trails both impact natural resources, informal trails tend to be poorly constructed and located, posing a considerable threat to natural resources (Marion & Leung, 2011; Wimpey & Marion, 2011a). Just a limited number of visitors is needed to create visible informal trails, with only a few passes on the same surface tread required to potentially impact species (Thurston & Reader, 2001; Wimpey & Marion, 2010). If the corridor of an informal trail is visible, it can induce visitors to follow the same route, not knowing whether its design is formal or informal (Wimpey & Marion, 2011b). Informal trails often result from a failure to satisfy the expectations of visitors of formally constructed trail systems. Hence, recreationists might walk off-trail, starting the formation of an informal trail network. The development of informal trails underlie a variety of reasons, ranging from adventure-driven experience, such as mountain biking off-trail into more challenging terrain or explorational hiking tours, as an evasion or simply as a connection between formal trails (Marion & Wimpey, 2007).

In some cases, free riding mountain bikers deliberately create informal trails. Especially in areas with; a high population density, limited natural settings, limited rough challenging terrain, and minor or non-existent mountain bike trails, adventure-driven proliferation of informal trails is present. Mountain bike riders tend to construct informal trails and user-created trail technical features, so called TTFs, to enhance technical challenge (Davies & Newsome, 2009; Leung et al., 2014; Pickering et al., 2010b). Off-trail mountain biking can cause additional impacts such as soil compaction, erosion, vegetation damage and the entry of foreign material into natural recreational area (Davies & Newsome, 2009). Even though, the construction of informal trails is visible and increasing, there is limited scientific research on the effects and impacts of off-trail mountain biking (Pickering et al., 2010b).

However, not only user specific informal trail impacts, but also other impacts of informal trail proliferation, such as the extent to which informal trails may cause landscape fragmentation, have received limited research attention. Fragmentation is a process, which leads to the isolation of habitat patches within an ecosystem or landscape, encircled by industrialized and urban areas (Forman, 1995; Geneletti, 2004). Many environmental impacts are associated with fragmentation; including a reduction of the ability of plants and animals to disperse, changes in population dynamics and animal behaviour and reduction in habitat area and quality (Jaeger, 2002; Mazerolle et al., 2005). Linear infrastructures, such as trails are known to contribute to habitat fragmentation, acting as linear barriers or elements of disturbance for wildlife (Geneletti, 2004). In particular, the proliferation of informal trails is seen to be a major source of trail-based-fragmentation, decreasing habitat area and mean fragment size (Leung et al., 2011; Wimpey & Marion, 2011a).

Due to their ecological significance, informal trails have been selected as the focus of this research. This thesis assesses the impacts of informal trail networks and their potential of fragmenting forested areas in three study areas close to Zuerich, Switzerland, with a total area of 23.84 km^2. Due to the identification of type of use on informal trails, comparisons are made between the characterizations of trail segments and impacts caused between mountain biking and other recreational activities. To evaluate the impacts related to off-trail mountain biking, trail technical features are included in the evaluation. Furthermore, this work assesses the potential effects of informal trail proliferation on wildlife, by incorporating data on twelve monitored roe deer in one study area.

1.2 Research objectives

The main objective of this thesis is to gather information about the characteristics, extent and distribution of informally created trail segments and to assess their impacts in three forested areas close to Zuerich. This thesis explores impacts of informal trail networks by assessing the length and density of informal trails, total disturbed area and trail-based fragmentation. Furthermore, differences between informal trails used exclusively by mountain bikers and those used by other user types are investigated. To assess the impacts caused by off-trail mountain biking, trail technical features on or adjacent to informal trails are recorded and characterized.

Specifically, this research seeks to enhance our understanding of informal trails by answering the following questions:

1. *How does informal trail proliferation affect three peri-urban forested areas close to Zuerich and what are the characteristics of the informal trail segments?*

2. *To which extent do informal trails contribute to landscape fragmentation within three peri-urban forested areas close to Zuerich?*

3. *How do informal mountain bike trails and associated trail technical features affect three peri-urban forested areas close to Zuerich?*

4. *Are there differences in informal trail characteristics among trail segments used exclusively by mountain bikers and segments used by other user types?*

1.3 Study significance

Limited research has focussed on mapping or investigating resource impacts caused by informal trail networks within protected areas (Barros et al., 2013; Leung et al., 2011; Wimpey & Marion, 2011a). Previous research has drawn comparisons between formal and informal trail networks (Ballantyne & Pickering, 2015) and assessed the spatial characterization of informal trails in connection with visitor use and motivations of their development (Walden-Schreiner & Leung, 2013). However, only a few studies have mapped and investigated informal trail proliferation outside of protected areas (Walden-Schreiner & Leung, 2013). The dearth of comprehensive research on the impacts of informal trails is surprising, considering the threats they can pose (Wimpey & Marion, 2011a).

Diverse negative environmental impacts are known to be a result of the creation of informal trail networks, including additive disturbance area to the existing formal trail system (Wimpey & Marion, 2010). Monitoring of informal trail networks provides information about the lineal extent, areal distribution and informal trail conditions. From a management perspective, this information can be essential for detecting resource degradation and habitat fragmentation and can be used to effectively take action and by doing so minimize its impact (Marion et al., 2006). To date, there is no inventory assessment of informal trail networks in the Zuerich area. This study will provide information about informal trail location and characteristics. Documenting the extent and characteristics of informal trail segments will help managers to minimize current impacts and to reduce further damage caused by recreational use. The information will be displayed in maps and can serve as a basis for land managers to gain spatial knowledge about informal trail networks in their area. Further, this data can be used for identifying informal trails in vulnerable areas and specific management implications can be set up to minimize or prevent usage. This research can serve as a foundation and kick-off point to study user-created trails and to learn about motives and experiences recreational visitors are seeking. Additionally, this thesis aims to advance the current understanding of impacts caused by off-trail mountain biking by including trail technical features into the assessment methodology and by assessing whether differences between informal trails by user types exist.

2 Literature review

2.1 Trails in landscapes

2.1.1 Formal trails

Trails are basic and essential components in environmental and outdoor recreational settings. They are an integral infrastructural and recreational feature in natural environments, by providing access to areas with little or no road access (Marion & Leung, 2011; Wimpey & Marion, 2011a).

Formal trails can be defined as trails, which are designed, constructed and maintained to provide access to formerly inaccessible areas and to concentrate visitor traffic to designated tread surfaces (Marion & Leung, 2011; Wimpey, 2009; Wimpey & Marion, 2011a). Professional trail construction includes the removal of surface vegetation and organic litter. By this process, the underlying mineral-soil layer is exposed, shaped and hardened to drain water and to provide safe and durable surfaces (Wimpey, 2009). On natural surfaced trails, however, the process of uncovering the soil-layer can result in diverse resource impacts, such as soil compaction and erosion, muddiness and trail widening (Marion & Wimpey, 2011).

Most formal trail systems are designed, constructed and maintained to guide visitor traffic and to accommodate high visitor numbers, while minimizing visitor impacts to natural areas (Leung & Marion, 1999; Marion & Leung, 2004; Marion & Leung, 2011; Wimpey, 2009; Wimpey & Marion, 2010). Well-designed trails avoid grades steeper than 10% to limit soil erosion and avoid “fall-line” alignments (IMBA, 2004; Wimpey and Marion, 2011a). Trails with alignments parallel to slopes are difficult to drain water from and are more susceptible to soil erosion (Marion & Leung, 2004; Olive & Marion, 2009). The location and design play an important role in reducing trail impacts. Many problems related to trail degradation are a result of poor planning, construction and management (Marion & Leung, 2004). Therefore, the lack of proper trail design makes them susceptible to degradation (Farrell & Marion, 2001; Marion & Leung, 2004).

Visitor-related impacts on and off-trails can vary in type and severity. Impacts of recreational usage on formal trails include; damage to existing trails such as trail widening, changes of trail surfaces, root exposure, loss of organic litter, soil compaction and muddiness (Marion & Leung, 2004; Pickering et al., 2010a, Wimpey, 2009). However, trail widening can substantially lead to increased soil erosion, changes in hydrology and to the spatial expansion of the disturbance (Marion & Leung, 2004; Wimpey, 2009). Further, there can be damage to plants including compositional changes, introduction and spread of invasive species, weeds and pathogens. Other impacts include disturbance of wildlife, increased habitat fragmentation and the creation of informal trails (Marion & Leung, 2004; Pickering et al., 2010a; Wimpey, 2009.)

In well-designed cases, trails build the perfect setting for a variety of outdoor experiences and enjoyable recreational activities (Wimpey, 2009). However, in some cases, formal trails fail to satisfy the recreationists' need to see various locations or to provide the recreational experience they are looking for (Marion et al., 2006; Marion & Leung, 2011; Wimpey & Marion, 2011a). In this case, recreationists might wander off-trail to reach formally inaccessible locations (Wimpey, 2009; Wimpey & Marion, 2011a).

For this thesis formal trails are trails, which are designated in the topographic map 1:25 000 of the Swiss confederation.

2.1.2 Informal trails

Informal trails can be defined as distinguishable and continuous visitor created trail segments (Leung et al., 2002). They are also known as social or unofficial trails and are commonly poorly designed and located. Informal trails are neither maintained nor included in the formally managed trail system (Leung et al., 2002). Informal trails can exist in various forms, ranging from dense accumulations of short tracks to trails with extensive length (Marion et al., 2006).

Both informal user-created trails and formal trails impact the environment depending on the type of trail usage, its construction, user frequency, location, surface condition and trail management (Marion & Leung, 2011; Wimpey & Marion, 2011a).

Even though, in some cases informal trails are indistinguishable from formal ones, informal trails can differ in a variety of ways from their formal counterpart (Walden-Schreiner & Leung, 2013; Wimpey & Marion, 2011a; Wimpey & Marion, 2011b). In comparison to most formal trails, informal trails are unplanned, poorly located, not professionally constructed nor maintained or managed and therefore may contribute to greater resource degradation in comparison to formal trails (Marion et al., 2006; Marion & Wimpey, 2007; Marion & Leung, 2011; Wimpey & Marion, 2010; Wimpey & Marion, 2011b). Generally, informal trails are characterized by a large variance in width, poor surface conditions, a high degree of soil erosion, muddiness and poor slope alignment (Ballantyne & Pickering, 2015; Wimpey & Marion, 2011b). Informal trail networks can reach extensive dimensions and can array in complex networks within an area (Marion et al., 2006; Wimpey, 2009). The development of informal trails can be due to several causes. Reasons might be to reach locations, which are inaccessible by the formal trail network, to evade muddy conditions or an accidental exiting of the formal trail network due to poor formal trail marking. Further, informal trails can act as shortcuts or linkages between formal trails or can be constructed to satisfy goal-driven behaviours of recreationists, such as bike-riders longing for more challenging terrain (Wimpey & Marion, 2011a).

Due to the lack of professional construction, design and maintenance, resource impacts of informal trails can be severe and even greater than formal trail impacts (Marion & Wimpey, 2011). Informal trail impacts can entail vegetation loss in height and cover, changes in plant composition, seed dispersal, fungal pathogen transport and browsing of shrubs and vegetation. Further impacts include soil erosion, degradation of water resources, fragmentation of habitats, wildlife displacement and disturbance (Barros et al., 2013; Cole, 1995; Marion & Leung, 2001; Marion et al., 2006; Wimpey, 2009; Wimpey & Marion, 2011b). However, only a low level of usage is needed to create visible informal trail treads and to cause damage by removing layers of vegetation cover and organic litter (Cole, 1993; Cole, 2004; Thurston & Reader, 2001; Weaver & Dale, 1978). According to Marion & Leung (2001), low levels of use cause the highest share of use related impacts.

Thus far, very few studies have mapped and assessed the impacts of informal trails within natural areas (Barros et al., 2013; Davies & Newsome, 2009; Marion et al., 2006; Wimpey & Marion, 2011a). Some researchers focussed on the comparison of formal and informal trail characteristics (Ballantyne & Pickering, 2015; Wimpey & Marion, 2011a).

Wimpey & Marion (2011a) focused on the spatial characterization of informal trail networks and examined formal and informal trails within the Great Falls Park in Virginia. The researchers mapped and characterized the informal trail system and compared it with the existing formal trail system, including their topographical alignments. They found out that informal trails have less sustainable topographic alignments, have higher grades and are located in steeper terrain than their formal counterparts. Furthermore, informal trails tend to be narrower and are more likely to be aligned to the “fall-line”. Hot-spot analysis revealed that highest informal trail densities are located at spots, which give access to vista from the cliff-top. The authors suspected numerous additional motives of informal trail creation, such as access to points within an area not reached by formal trails, avoidance of conditions such as muddiness, exploration, accidental, shortcuts, attraction, and activity-based informal trail construction by engaging in off-trail recreational activities.

A study conducted by Ballantyne & Pickering (2015) investigated the differences in the impacts of formal and informal recreational trails on forest loss and tree structure. In comparison to formal trails, informal trails were generally poorly designed, located and had poorer trail surface conditions with higher soil loss and width variation. Structural impacts to the forest varied by type of recreational trail, with wide informal trails and hardened formal trails resulting in comparable reductions in tree density and canopy cover. The loss of forest strata and the tree structure differed among trail types. Large formal and informal trails had a similar loss of forest strata and in comparison to narrower trails the greatest loss. However, according to the authors, informal trails could pose a higher threat to forest loss due to the tendency to widen over time.

A research team around Agustina Barros focused on the impacts to vegetation of informal trails in the Aconcagua Provincial Park in South America (Barros et al., 2013). The impacts of informal trails on vegetation and soil were investigated along the main access route to the Mount Aconcagua summit. Impacts were compared between alpine steppe and meadows. The creation of informal trails by hikers and pack animals has resulted in vegetation damage and soil erosion. Higher soil loss and more vegetation damage were visible in the alpine meadows than in the alpine steppe vegetation. The alpine meadow vegetation lacks woody vegetation, which restrict recreational traffic and trampling effects to narrower trails. Additionally, plants in dry sites are less sensitive to recreational impacts than plants growing in wet soils, like on the alpine meadow sites. Impacts of recreational activities in Anconcagua are not limited to soil loss and vegetation damage, but can affect changes in soil moisture and microclimate. According to Barros et al. (2013), more research is needed to assess diverse effects of recreational activities in Anconcagua.

A study conducted in the Yosemite National park addressed the development of informal trail indicators by integrating spatial information on visitor distribution (Walden-Schreiner & Leung, 2013). Data was collected in three Yosemite Valley meadows. Researchers revealed a high cluster of visitor use in areas close to specific locations and popular visitor attractions on formal trails or adjacent. The small percentage of visitor use of informal trails indicates that visitors tend to choose the formalized option when given a choice. When off-trail wandering occurred, observation revealed that visitors tend to use only a few informal trails. Both, type of activity and visitor motivations tend to influence informal trail behaviour.

Informal trail creation and proliferation pose a threat to natural resources and pose a challenge to land managers (Walden-Schreiner & Leung, 2013; Wimpey & Marion, 2011a). In comparison to formal trails, informal trail networks raise a greater management concern. They are more susceptible to impacts due to their complexity, poorer design attributes and close proximity (Wimpey & Marion, 2011a; Wimpey & Marion, 2011b).

For this thesis, an informal trail is defined as a user-created unmanaged trail, with the starting point located on a formal or other informal trail and the endpoint located either on a formal or informal trail or leading to a specific point of interest. They are neither designated in the formal trail system of the topographic map 1:25 000 of the Swiss confederation, nor planned or approved by land managers. Only informal trails with a length of more than 10m were recorded. Skid roads were only included if their use by recreationists was visible.

2.1.3 Trail based fragmentation

Landscape fragmentation caused by humans such as urbanization, road construction, land use change and other anthropogenic influences lead to a decrease in non-fragmented habitat patches and increased isolation of wildlife populations (Forman, 1995; Geneletti, 2004). Anthropogenic fragmentation is known to be a major threat for small susceptible endangered populations of certain species. Recreational activities and the infrastructures provided for them can contribute to the process of human-induced landscape fragmentation.

Internal fragmentation within a specific area, such as trail-based fragmentation, has received limited research attention in comparison to the effects of external fragmentation in natural areas (Ballantyne & Pickering, 2012). Recreational infrastructures, such as trails, with their descriptive linear geometry, can act as barriers for certain species and decrease the number of non-fragmented and undisturbed habitat patches (Geneletti, 2004; Leung et al., 2011; Pickering & Castley, 2012). Furthermore, trails can influence movement patterns of species and reduce or even prevent gene flow (Ballantyne et al., 2014b). Therefore, trail networks can pose a threat to wildlife by exacerbating disturbance. Trails can reduce native seed dispersal especially for species with short dispersal distances. Additionally, trails can serve as conduits for invasion of exotic species (Benninger-Truax et al., 1992; Drayton & Primack, 1996; Forman, 1995).

Informal visitor-created trails can exacerbate the process of fragmentation (Leung & Pickering, 2012a). In comparison to their formal counterparts, fragmentation effects can be greater for informal trail segments (Ballantyne et al., 2014a; Leung et al., 2011; Wimpey & Marion, 2011a). By providing access into former undisturbed landscapes and habitats, informal trails can enhance the effects of trail-based fragmentation and pose a threat to vegetation and wildlife (Leung et al., 2011; Pickering & Castley, 2012). Informal trails can contribute to the fragmentation of wildlife habitat, reducing formerly continuous habitat area. Furthermore, the use of informal trails has the potential to impact behavioural patterns of animals. A stronger response of wildlife to the presence of humans is visible when humans are using informal trails (Taylor & Knight, 2003). Thus, the impact of informal trails to wildlife might even be of more concern than impacts by formal trails. Due to different spatial extent and distribution, informal trails can influence fragmentation effects differently (Leung & Pickering, 2012b).

2.1.4 Informal trail assessments

Trail assessments provide information about trail characteristics and can include condition, location, type of trail impacts and linear extent of the trail network. In many cases they are used in supporting management considerations (Marion & Leung, 2001). Informal trails have been assessed and monitored by a number of researchers (Barros et al., 2013; Cole, 1983; Leung et al., 2011; Wimpey & Marion, 2011a). Even though the extensive and complex structure of informal trail networks can pose a problem to the efficiency of field assessments (Marion et al., 2006), a variety of assessment and monitoring methods have been applied to informal trail networks, including sampling-based- and census-based-approaches and informal trail extraction from georeferrenced imagery (Boorman & Fuller, 1977; Cole, 1983; Cole, 1991; Marion et al., 2006).

Sampling-based approaches assess trail conditions either by systematic point sampling, where trail assessments are conducted at a fixed interval along a trail (Cole, 1983; Cole, 1991) or by stratified point sampling, where the sampling is conducted according to various strata (Hall & Kuss, 1989). In comparison, census-based approaches employ either a sectional evaluation or census the entire trail system (Cole, 1983). To employ sectional evaluation, trails are divided into sub-segments. Sectional evaluations assess trail characterization and features for an entire trail section, often including qualitative rating and quantitative measures (Bratton et al., 1979; Marion & Leung, 2011).

Census-based approaches require extensive field inventory or mapping using GPS devices (Marion & Leung, 2011). Census surveys have the advantage of being able to generate maps of trail networks, showing the location and spatial arrangements of various informal trail segments, recording the number of segments and in calculating the lineal extent of the informal trail network. Additionally, the collected data can also be used, e.g. for evaluating landscape fragmentation and area of disturbance, by making use of Geographic Information Systems (GIS) (Wimpey & Marion, 2010). Problem census-based approaches assess trails continuously, recording the occurrence of predefined problems (Cole, 1983; Leung & Marion, 1999). A precise problem definition is important. A problem based trail assessment can include the recording of number and length of predefined problems along a trail and the mapping of the location of each occurrence (Cole, 1983). Further it can include assessing the start and endpoint of trail segments, which are excessively impacted by these problems (Marion & Leung, 2011).

2.2 Mountain biking

2.2.1 Overview

Recreational use of areas in natural settings is growing worldwide (Monz et al., 2010). In times of an increase in recreational activities, mountain biking puts pressure on natural areas as an additional recreational activity (Chavez et al., 1993; Symmonds et al., 2000; Thurston & Reader, 2001). Within the last forty years, mountain biking has gained great approval among recreational activities with a continued increase in participation within Europe (Pickering et al., 2010b).

As mentioned in 2.1.2, one potential reason for the creation of informal trails is the demand of mountain bike riders for more challenging trails and terrain. In some cases, the response of land managers is too slow to react to the increasing demand for mountain biking facilities (CALM, 2007). Even though, mountain bikers are just one user type of informal trails. Informal mountain bike trails can differ from other informal trails by the construction and use of trail technical features (Davies & Newsome, 2009).

Like all trail usage, mountain biking affects the present environmental setting, causing some degree of change to natural resources (Cessford, 1995a; Cessford, 2002; IMBA, 2007; White et al., 2006). Informal mountain bike trails however, can cause significant damage to the environment (Ballantyne et al., 2014a; Foreman, 2003). In comparison to other informal trails, informal mountain bike trails can result in a higher impact by incorporating trail technical features.

Since its inception, mountain biking has caused management concerns (IMBA, 2007; Thurston & Reader, 2001). However, contrary to other recreational activities, limited research attention has focussed on mountain biking in the past decades (Hopkin & Moore, 1995). Most mountain bike specific research has concentrated on social issues associated with multiple-use conflicts, comparison between user groups, rider characteristics, user preferences and possible management implications. Therefore, a relative dearth in understanding the effects of mountain biking to the natural environment and a lack of knowledge about the extent of change to natural resources is apparent to date (Goeft & Alder 2001; IMBA, 2004; White et al., 2006). Supplementary impacts by the creation of informal trails and attributed trail technical features to resource degradation and the environment have rarely been studied (Marion & Wimpey, 2007).

The following paragraphs give an overview about the history of mountain biking, rider preferences and settings, and about environmental impacts of mountain biking in natural areas.

2.2.2 History and development

Mountain biking is a relatively young and rapidly growing outdoor recreational activity. It can be defined as the sport of riding specially designed off-road capable bikes, typically on unpaved environments and often over rough and steep terrain. This variety of biking has its special attraction in riding on small-unsecured roads in untouched nature, far away from traffic-jammed streets. Mountain biking is diverse and can be combined with different levels of physical fitness and user preferences. It connects fun and independence for the rider within a natural setting.

The historical development of mountain biking began in the 1970s in the United States, in California (Manley, 2014). A group around Gary Fischer, Charles Kelly and Joe Breeze, today recognized as the founding fathers of mountain biking, used 1940s klunkers to ride off-road (Manley, 2014; Natter, 2009). To be able to ride off-track, the pioneers modified the street bikes by mounting fat tires on steel rims. In 1974, the first official off-road bike with a weight of 19kg was developed by Fischer and Kelly (Manley, 2014). Soon afterwards, the company MountainBike was founded by Fisher and Kelly and the first mountain bikes were produced for sale, using frames developed by Tom Ritchey (Natter, 2009). In 1981, Mike Synard started the first mass production with the „Specialized Stumpumper" bikes for the international market and sold it around the world. (Manley, 2014; Natter, 2009). Further manufacturers followed. New technologies and technical advances, such as lighter material for frame construction, suspension forks and more efficient gear shifting and better suspension, appeared. In the 1990s mountain biking was acknowledged globally and experienced a vigorous increase in participant numbers (Kesteven, 2014). Nowadays, the mountain biking sector is rated among the most important ones within the biking industry (Natter, 2009).

2.2.3 Mountain biking types and rider preferences

Within the last forty years, mountain biking has developed towards an independent sport with a significant diversification of categories and the emergence of several user types. Depending on the skill, exercise and motivation of the rider, as well as the equipment used, a broad spectrum of mountain biking activities can be distinguished (Goeft & Alder, 2001). In order to manage recreational areas effectively, it is important to understand the different needs and impacts attributed to mountain bike styles (Chavez et al., 1993).

Even though several riding styles are defined, their categorization is subject to change. It does not cover the continuous development of new types of mountain biking styles (Hofer, 2003). Overlapping similarities between styles are visible, with riders participating in more than one category (IMBA, 2007). The International Mountain Biking Association (IMBA) defined several mountain biking categories in 2007: Cross country riding, all-mountain riding, downhill, dirt jumping and free riding. Disciplines such as Radquer and BMX are defined as independent categories (Gösele-Koppenburg et al., 2008).

The following paragraphs give a rough overview of riding styles of mountain biking.

Free Riding

Free riding occurs in particular off-trail, on challenging terrain or on specially designed single trails (Hofer, 2003). Riders favour challenges defined as trail technical features such as jumps, logs, rocks, drop-offs, berms and bridges (IMBA, 2007). Free riders use full-suspension bikes (Hofer, 2003).

Due to the characteristics of free-riders to include trail technical features into their experience and to challenge themselves by riding off-trail, this study refers primarily to free-riding mountain bikers.

Cross Country Riding

Variation of rider types from beginners to experienced riders. Avid mountain bikers usually look for a trail combination ranging from 16-160km. Cross-country riders prefer short-travel light weight suspension bikes (IMBA, 2007).

All-mountain riding

Similar to the variation in experience in the cross-country discipline, all mountain riding includes everything from novices to highly skilled riders. Riders in this category seek technically challenging trails and are usually equipped with longer-travel suspension and durable bikes (IMBA, 2007).

Downhill Riding

Goal for riders in this category is to clear highly technically challenging trails as fast as possible. Usually downhill trails are cordoned off from public usage and are specifically designed for downhill purposes. Riders in this category prefer heavy bikes with full-suspension and use full body protection (Hofer, 2003). Ski areas often provide facilities for downhill-biking in summer (IMBA, 2007).

Dirt Jumping

Dirt jumpers seek the air experience and look for jumping opportunities. Riders in this category use a variety of bikes (IMBA, 2007).

Rider characteristics were assessed in various studies conducted in the last two decades

(Cessford, 1995b; Chiu & Kriwoken, 2003; Goeft & Alder, 2001; Heer et al., 2003; Hollenhorst et al., 1995; Hopkin & Moore, 1995; Horn, 1994; Symmonds et al., 2000). According to the results of these studies, the average mountain biker tends to be predominantly male, around 30 years old (except for the results of Chiu & Kriwoken (2003), where the age was evenly distributed between 16-45) and highly educated. Mountain bike riders are physically fit and seek to challenge themselves to improve their condition and riding skill (Horn, 1994).

Mountain biking research reveals a diverse variety of riding preferences. Settings and trail preferences differ according to the individual skills of the biker (Hopkin & Moore, 1995). Generally, mountain bikers prefer trails in natural settings such as native forested areas, rather than urban environments (Hopkin & Moore, 1995; Leberman & Mason, 2000). Novice riders prefer to ride on smooth and wide tracks with good sight in trail direction (Chiu & Kriwoken, 2003). Whereas, more experienced riders prefer steep downhills, long curves, winding trails, narrow tracks, tight curves, obstacles (jumps, rocks, logs), short uphill sections and rough or muddy surface (Chiu & Kriwoken, 2003; Goeft & Alder, 2001; Hopkin & Moore, 1995; Leberman & Mason, 2000). According to Leberman & Mason (2000), favourable riding conditions are a combination of up- and downhills on narrow trails, preferable single tracks, with technical challenges, such as logs, rocks and other forms of obstacles. Average riding times for weekly excursions ranged between two to three hours (Leberman & Mason, 2000).

Mountain biking activities are generally pursued in mountainous areas on forest roads, hiking tracks and specific biking trails. Most mountain bikers prefer to ride on roads and trails, as this enables easier locomotion and offers fewer obstacles (Jakob et al., 2002). Only small numbers of riders seek the experience of challenging their riding ability in off-trail terrain (Wöhrstein, 1998).

2.2.4 Environmental impacts of mountain biking

Environmental impacts of mountain biking can be distinguished broadly into the impact categories: soils, vegetation, water and wildlife (Cessford, 1995a; Davies & Newsome, 2009; Marion & Wimpey, 2007; White et al., 2006). Mountain biking is mainly conducted on trails. Therefore, most impacts are related to changes on the trail or close to it, such as trail widening, soil erosion, damage of adjacent vegetation, change in species composition, spreading of weeds and root exposure (Pickering et al., 2010a).

In contrast to the general perception, to date there is no evidence that mountain biking has a greater impact on the environment than other recreational activities such as hiking and horse riding (Cessford, 1995a; Chavez et al., 1993; IMBA, 2004; Marion & Wimpey, 2007;

Pickering et al. 2010a; Wöhrstein, 1998). No significant differences between hikers and mountain bikers were identified in erosion rates (Wilson & Seney, 1994) and impacts on vegetation and soil (Thurston & Reader, 2001). Impacts on vegetation and soil occurred for both activities within 30cm of the trail centreline (Thurston & Reader, 2001). According to Chiu & Kriwoken (2003), mountain biking and hiking cause a similar impact to natural areas.

However, Wöhrstein (1998) discovered that mountain biking has a higher impact going uphill, while hiking has greater downhill impacts. For bikers, the impact going downhill is less due to the lower wheel loading.

Unique impacts of mountain biking to the environment in natural areas are caused by intentional or unintentional braking and skidding. Skidding increases soil movement downslope and the rate of soil erosion. Additionally, it favours the formation of ruts, which contribute to erosive water runoff (Cessford 1995a; Davies & Newsome, 2009). If mountain bikers skid on- or off-trail, impacts of mountain biking increase in comparison to other recreational activities (Cessford 1995a; Chiu & Kriwoken, 2003). Mountain biking´s greatest damage is concentrated in the centreline of the trail (Chiu & Kriwoken, 2003).

Davies & Newsome (2009) conducted an exploratory literature review to examine the biophysical and social impacts of mountain biking to provide a base for an impact assessment methodology. With this background, they developed an assessment method to measure the extent of informal trails and trail technical features, created by mountain bikers. Within this research, a Global Positioning System (GPS) and Geo Information System (GIS) assessment method was used to identify and quantify the informal trail network in the John Forrest National Park in Perth, Australia. In conclusion, Newsome & Davies identified three important impacts of mountain biking to natural areas, including trail erosion, construction of informal trails and the additional creation of informal trail technical features. The researchers identified on- and off-trail impacts. Off-trail impacts included the creation of informal trails, construction of trail technical features and reduced amenity.

The severity of impacts caused by mountain biking can vary according to trail characteristics, geographical location and riding styles (Davies & Newsome, 2009; Goeft & Alder, 2001; Pickering et al., 2010a). Riding on different surfaces and the surface conditions lead to variations in impact severity (Chiu & Kriwoken, 2003). Impacts of mountain biking are likely to increase in wet conditions and on steep slopes, where the occurrence of wheel-slip is higher than on dry surfaces (Cessford, 1995a; Chiu & Kriwoken, 2003; Wilson & Seney, 1994).

Davies & Newsome (2009) identified the creation of informal trails as an off-trail impact of mountain biking. Due to the nature of mountain biking, riders might tend to construct informal trails deliberately by riding off-track. However, in some cases the informal trail does not fully satisfy the demand of the rider with regards to technical difficulty. In these cases trail technical features might be constructed, causing an additional environmental impact.

Within this thesis, the term, off-trail mountain biking, solely refers to mountain biking off formal trails, using informal trails. It does not include riding off-trail (formal and informal) over free and “untouched” terrain.

2.2.5 Trail technical features (TTFs)

Trail technical features are obstacles, which are constructed on or beside trails to enhance the technical challenge for riders. Examples of trail technical features are rocks, logs, bridges, jumps, drop-offs and many more. The height and the width of each feature can vary according to the trail difficulty (IMBA, 2015).

The research on the environmental impacts of off-trail mountain biking and the potential contribution of trail technical features to resource degradation remains limited (Marion & Wimpey, 2007). Newsome & Davies (2009) defined and categorised mountain bike specific social and biophysical impacts, such as the creation of informal trail networks and human-made trail technical features. They recognised trail technical features and informal trails as a key challenge for management issues.

Pickering et al. (2010b) developed the first detailed assessment methodology incorporating trail technical features in an impact assessment of mountain biking. The assessment consisted of 24 attributes, categorised into four categories: TTF characteristics, site details, environmental impacts and management and safety related issues. The study was carried out in an endangered forest remnant on the Gold Coast in South East Australia. The researchers used a mixture of qualitative and quantitative parameters to assess the potential environmental, safety and management-related issues associated with the presence of trail technical features. Data from 116 trail technical features were analysed. The study revealed that the construction of trail technical features contributes to environmental degradation by affecting vegetation and soils. Soil movement and areas without understory and trees were visible. Furthermore, the incorporation of foreign material and harvesting of timber were additional impacts. Environmental impacts directly associated with the construction of TTFs were: damage to existing vegetation, exposure of bare ground and movement of soil, tree harvesting, introduction of materials and the presence of rubbish around the TTF. These impacts add to the effects of the construction of informal trails.

Kollar (2011) modified the assessment methodology of Pickering et al. (2010b) by applying a different sampling design and additional attributes. The assessment was carried out in two urban-proximity study areas in the United States. A coastal mountain biking site located in

North Carolina and a montane site in Montana were compared. Kollar used a more specific characterization of TTFs by using a technical opportunity framework and dividing TTFs into ground, traverse or aerial groups. To identify the biophysical impacts of each TTF, a circular observation method was applied assessing the impacts in a metric defined area depending on the length of the TTF. Trail technical features have an effect on the environment. However, some indicators, such as root exposure and trail incision are more significant for the assessment of direct impacts of TTFs. The study revealed that the biophysical impact caused by TTFs varies according to the specific feature type.

3 Material and methods

3.1 Study sites

The assessments were conducted in three peri-urban forested study areas close to Zurich, Switzerland. The main study area covers 23.84km^2, with elevations ranging from 450m to 915m. The study sites are located in the Sihlwald area in the South, the Adlisberg in the East, and at the Zürichberg to the North-East of Zuerich. Furthermore, in order to assess potential impacts of informal trails on wildlife by using roe deer as an example, additional study area patches were included, comprising an area of 3.39km^2 (Figure 8.1), summing up to a total area of 27.23km^2. The main study areas are depicted in Figure 3.1.

The Sihlwald study area encompasses an area of 14.19km^2, and is located at 47°15'9'' N, 8°33'16''E, with elevations ranging from a minimum of 467m to a maximum of 915m. The study area includes the natural forest Sihlwald, which is included in the Wildnispark Zurich, consisting of the Sihlwald and the Langenberg. The Sihlwald has been developed into a natural forest over the last ten years and is divided into a core zone (41%) and a nature experience zone. The core zone was established to enhance the natural development of the forest. Rules apply within the core area including the sole use of formal trails, no gathering of plants and mushrooms and prohibition of campfires. Within the two zones user specific trails exist, giving users the opportunity of enjoying nature on specific hiking, mountain biking and horse riding trails. 70km of hiking trails, 51km of biking trails and 41km of horse riding trails are designated within the boundaries of the natural forest (Wildnispark, 2015). Due to the policy of staying on formal trails in the core zone, only informal trails in the nature experience zone were mapped.

The Adlisberg study encompasses forested area of 5.24km^2 and is located at 47°22'13''N, 8°35'39''E in the East of Zuerich, with the highest elevation of 701m and the lowest at 450m. This study area includes the forested areas at the Adlisberg, the Öschbrig and the Werenbach area. The perimeters for this study area were the city boundaries and the adjacent Zürichberg study area.

The study area Zürichberg is located at 47°23'27''N, 8°33'32''E, with elevations ranging from 456m to 676m. It encompasses the forested areas of the Zuerichberg, the area around the sports complex Flunders and the Wolfbach area with a total area of 4.40km^2. Perimeters were defined as the forest area within city boundaries and the adjoining Adlisberg study site.

Study areas for the roe deer assessment are located in and around the Sihlwald study area. The study area patches include the habitat of twelve GPS-collared roe deer and the locations are depicted in detail in the Appendix (Figure 8.1).

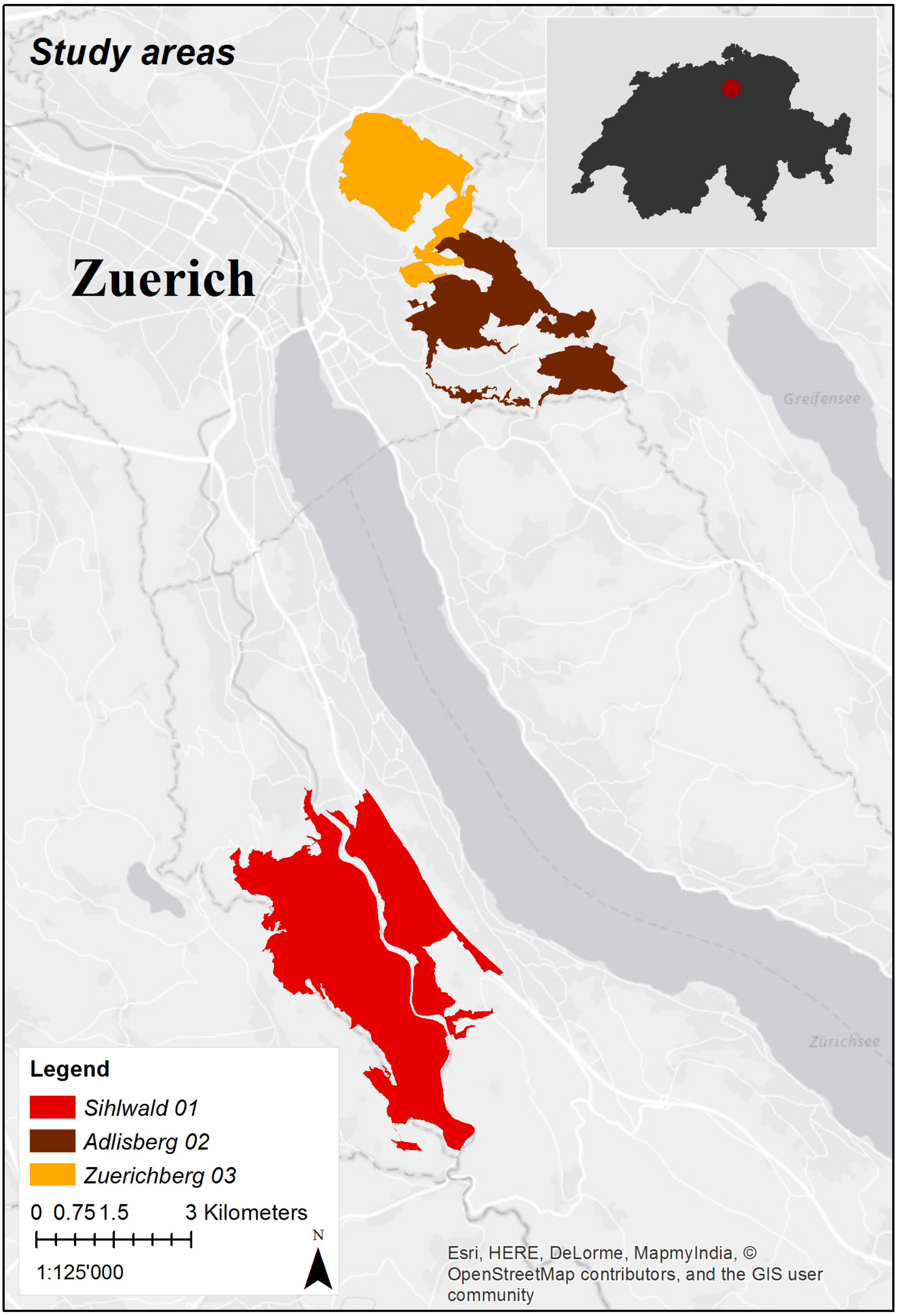

Figure 3.1: Study areas.

3.2 Assessments and data sampling

3.2.1 Informal trail assessment

The informal trail assessment included two types of monitoring protocols, combining an inventory survey and a census-based approach. According to Marion & Leung (2011), these survey types are ideal for assessing informal trail networks. Inventory surveys include the spatial collection of data with a GPS device to accurately map trail positions. Further, the GPS data can be processed in GIS for further analysis and map generation. Census-based surveys are common trail-assessment methods, which employ sectional evaluations (see 2.1.4).

Based on this background, an informal trail assessment was designed, using a mixture of 20 different quantitative and qualitative measures (Table 8.1(I-III)). The assessment included basic information about each informal trail; containing location (start and endpoint), trail width, side-effect of trail width, average slope and total length of each segment. Trail width is defined as the part of the trail, which supports the major part of visitor traffic (Wimpey, 2009). Side-effect of trail width includes the effects of trail widening, such as trampling of vegetation or removal of organic litter due to trail traffic. Both measures are depicted in Figure 3.2. The average slope expressed in percentage is equivalent to the average trail grade. The average slope is determined as the difference in elevation between two points divided by the linear distance between them, multiplied by 100 (IMBA, 2004).

Each informal trail segment was identificated by a unique ID representing the study area in which it is located and a consecutive number by which it can be distinguished from all other informal trail segments. The first informal trail segment in the Sihlwald study area was identified as 01-001-00-00. The first two digits represent the study area (Sihlwald 01, Adlisberg 02 and Zuerichberg 03), whereas the three ensuing numbers represent the unique ID of the present informal trail segment, starting with 001 in each study area. The following two digits were used for numbering the trail technical features and are referred to in 3.2.2.

If feasible, the user type utilizing the informal trail was recorded by assessing traces present on the informal trail segment. The user types were categorized as hikers, mountain bikers, horse riders, forest use and others. Due to the possibility of multiple trail usage, more than a single selection in user types was possible.

Quantitative measures, such as sight within and reverse trail direction, sight to the right and left side of the trail and maximum trail incision, were recorded. Qualitative measures included forest type, trail surface, mountain bike skid marks, damaged trees, root exposure, presence of rubbish and presence of signs to prevent usage. Forest type was categorized in deciduous, mixed and coniferous forest stands. The measure trail surface included the categories forest soil, sawdust, grass, roots, stones, gravel loose, gravel solid and other. Due to the possibility of the presence of more than one trail substrate, multiple selections were possible. Measures including skid marks, damaged trees, root exposure and presence of signs to prevent usage were assessed by recording whether they were present or not. Presence of rubbish was assessed by selecting from the following categories: None, appliances, vehicles, electronics, glass, metal, plastics and other. The categories were adopted from Pickering et al. (2010b).

The spatial and attribute data collection was conducted within a two-month period in early summer 2015. The data collection was conducted by the researcher herself with no further aid. To assess the potential impacts related to informal user-created trails, all informal trails, extending from the formal trail network, were identified within the boundary of each study area. The method required hiking the entire formal trail network within the study areas. In few cases, a bike was used to cover longer distances. Trail segments were mapped using a Garmin® Dakota 20 GPS, with accuracy ranging from 3m to 18m. Hence, trail impacts can vary according to the type of use (Marion & Leung, 2011). A new trail segment was assessed and recorded when the condition of trail surface, trail width or type of use changed. Localized changes of <10m were not included as an individual trail segment. Most data was recorded on a mobile device using the Geographical Open Data Kit GeoODK©, which provides a way to collect georeferenced data in the field (GeoODK, 2014). As a backup, paper forms of the surveys were taken into the field.

Point data of each informal trail segment were collected, recording the GPS starting- and endposition, as well as the altitude for both points. This information was used to ease the post-processing of the data. The average trail width and the side-effect of trail width was measured and estimated for the total trail segment by the collector (Figure 3.2). Maximum trail incision relative to the current tread was measured from the current trail tread boundaries to the lowest substrate surface. Quantitative measures were taken and qualitative measures were assessed according to the method displayed in Table 8.1 (I-III).

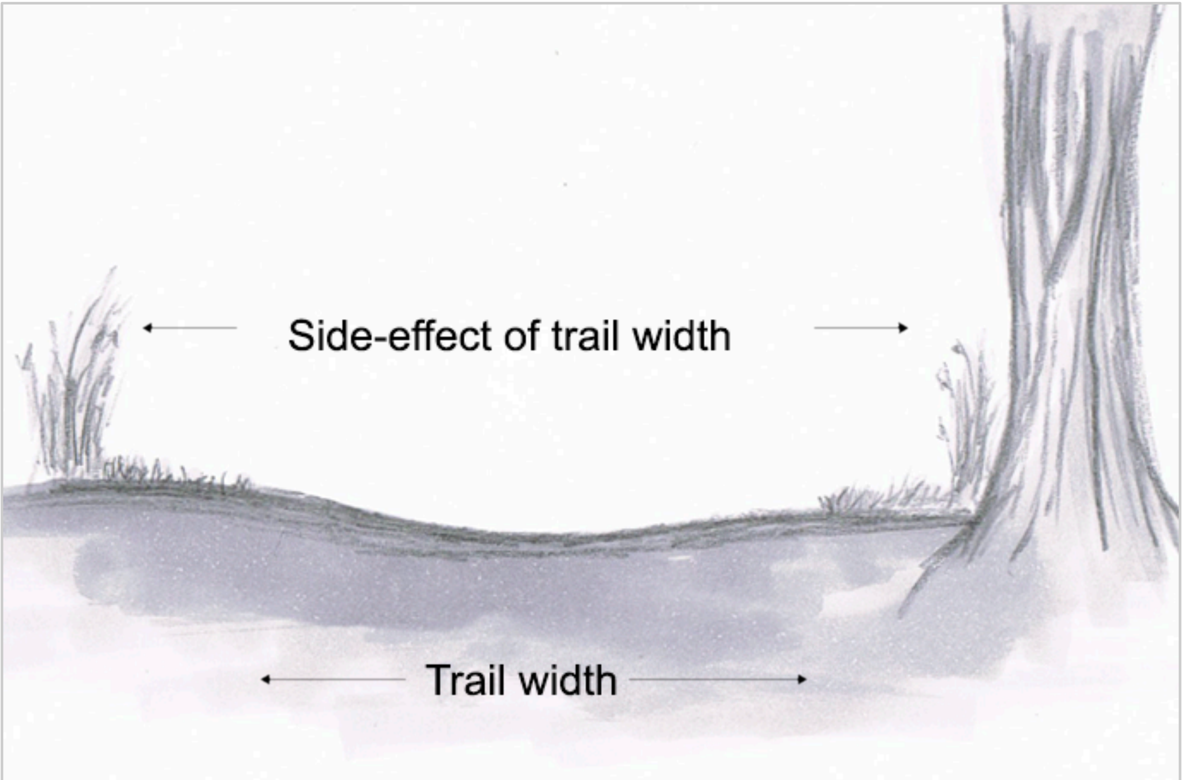

Figure 3.2: Trail width and side-effect of trail width. Source: Own diagram.

3.2.2 Trail technical feature assessment

To assess potential impacts related to mountain biking, trail technical features were assessed on encountered informal trails. The number and types of all features were recorded. The method used a similar approach to former trail technical feature assessments (Kollar, 2011; Pickering et al., 2010b). The assessment included 31 indicators, with a mixture of qualitative and quantitative measures (Table 8.2 (I-III)). It included basic information, such as the GPS location of each feature, TTF group, according to technical opportunity, type of structure, according to riding opportunity, and naturalness, size, construction material, location to trail, width of trail at feature, side-effect of trail width at feature, slope, aspect and whether the feature was rollable or not.

Each trail technical feature was identificated by a unique ID representing the study area in which it is located, the informal trail segment on which it is situated (or placed next to it) and a two digit number by which it can be distinguished from all other TTFs. The first TTF, situated on the first informal trail segment, in the Sihlwald study area was identified as 01-001-01-00. TTFs were categorized based on three technical opportunity groups: ground, traverse or aerial (Kollar & Leung, 2010). Ground TTFs are characterised as features, which offer a technical opportunity on a natural surface. Traverse TTFs offer a technical opportunity by traversing on an elevated surface. Aerial TTFs are characterized as features, which offer the rider the technical opportunity of leaving the ground (Kollar & Leung, 2010). According to the riding opportunity of the type of feature, each TTF was classified into bridge, camber, ditch, drop-off, berm, jump, ladder, bridge, ladder bridge, mound, log, see-saw, combination or other (Kollar, 2011; Pickering et al., 2010b). A pictured identification guide was made to be able to distinguish the TTFs easier in the field. The type of naturalness was assessed by recording whether the TTF is a natural, enhanced natural or artificial obstacle. Natural features are obstacles such as logs, which have been incorporated into the informal trail at the particular site without moving or modification. An enhanced natural feature is defined as a natural resource, replaced or recombined at the site. Enhanced natural features can even be brought to the site but have to be constructed from native natural resources. Artificial features are engineered and include foreign construction material (Kollar, 2011). Construction material was categorized in concrete, drums, local vegetation, metal, soils, imported timber and other (Pickering et al., 2010b). The location of each TTF was recorded by assessing whether it was situated on the track or in cleared vegetation.

Condition of the understory vegetation, the canopy type and ground cover were also assessed. The condition of understory was categorized in poor, good and thick vegetation and was categorized based on the judgment of the collector. The categories for the canopy type were defined as open (0-25% cover), mixed (26-74% cover) and closed (75-100% cover) and was also assessed according to the judgement of the collector. Ground cover was grouped in grass, saplings, needles, shrubs and adult trees. Multiple selections were possible.

Potential impacts of trail technical features were assessed by including the amount of disturbed area at the feature. Qualitative measures were recorded including the presence or absence of vegetation removal, root exposure, presence of rubbish and skid marks. Presence of rubbish was grouped in none, vehicles, electronics, glass, metal, plastics and others (Pickering et al., 2010b). Quantitative measures included the trail incision before and behind the TTF.

Safety factors and management issues were assessed by recording the condition and safety of features, as well as the presence or absence of signage, filters or choke points, fall zones, optional lines and the attempt to prevent usage. The condition of the feature was classed in low, poor, good and like new. The safety of the feature was classified as low, moderate, high and very high. The safety and condition of each TTF were grouped based on the judgement of the collector.

Different to Kollar (2011), the observation zone included all factors, such as optional lines (in length and width) and bare area of soil and/or vegetation, to assess the total amount of impact caused by the construction of trail technical features (Figure 3.3). The total area of disturbance included the entire affected area within the observation zone and the occupied area by the feature itself.

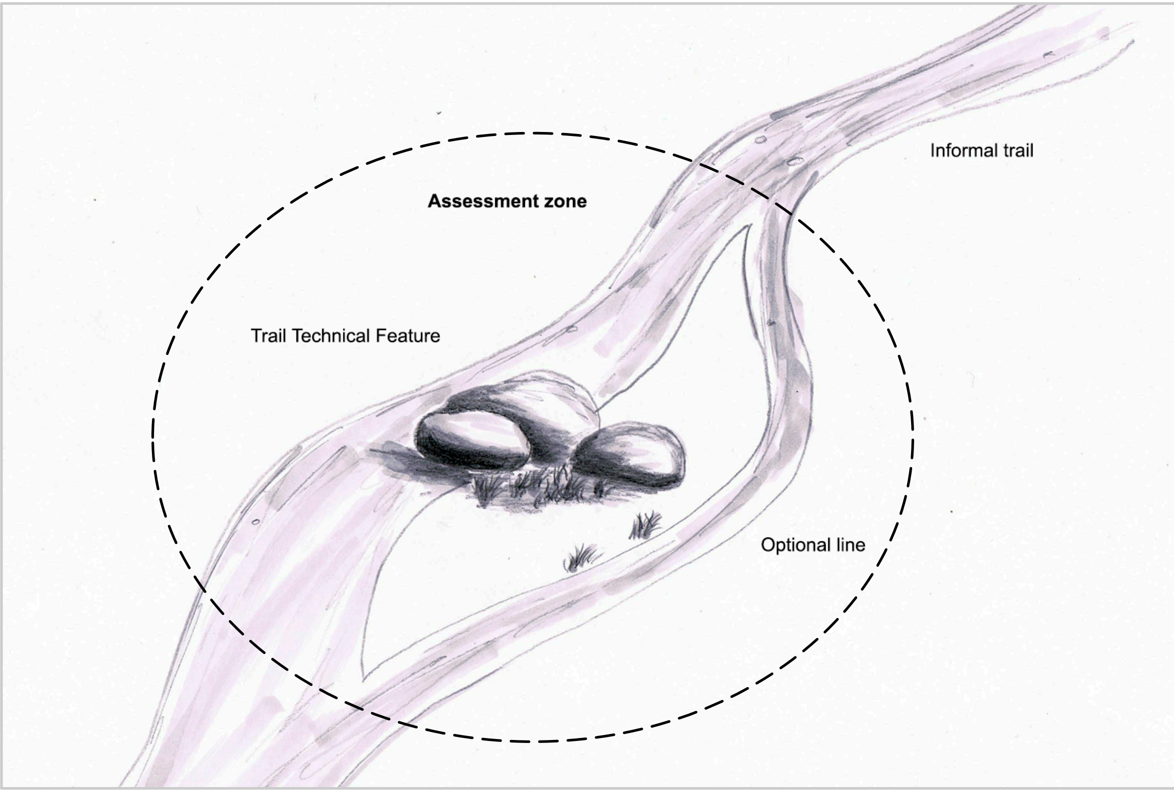

Figure 3.3: Trail Technical Feature Observation Zone. Source: Own diagram.

Initially, the main objective of this thesis was to identify impacts caused by off-trail mountain biking and associated trail technical features. After the relevant data was collected, the focus of the thesis was modified to impacts related to informal trail proliferation, due to the low amount of recorded trail technical features within the three study areas.

3.3 Data analysis

The informal trail mapping and the assessment of trail technical features resulted in point data. Informal trail segments were converted into line data, which then could be used to calculate indicators such as segment length, total linear extent of the informal trail network, total area of disturbance and landscape fragmentation using ESRI® ArcMap 10.3.1. For the analysis, the digital maps produced by the Swiss Federal Office of Topography called VECTOR25 (2008), at a scale of 1:25 000, were used.

3.3.1 Data preparation

The GPS information was post-processed using BaseCamp™, a program developed by Garmin to organise GPS data. Every single informal trail and each TTF was exported from BaseCamp and saved as a .gpx file for the later use in GIS. The additional information collected with GeoODK was uploaded to a Hub and downloaded as a Microsoft Excel® file. Due to separation faults, further manual editing was required. The resultant Excel spread sheets were saved as .csv files.

Post-processed GPS data were imported into ESRI ArcMap 10.3 and converted into point features using the “GPX to feature tool” for further editing and analysing. Due to different projection of the data, the point features were converted from WGS84 into the projected coordinate system CH1903 LV03 using the “Project” tool. Due to the spatial recording method of the Garmin Dakota, which records lines as time consecutive GPS points, the informal trail segments required extensive manual editing to create accurate line features, which represent the informal trail networks within the study areas.

In line with the legend of roads and trails published by the Swiss Federal Office of Topography, formal trails were categorised in forest roads, forest trails and hiking trails (Bundesamt für Landestopografie Swisstopo, 2014). Forest roads were defined as motorised roads with a minimum width of 2.8m. Forest trails were classified as motorised ways with a minimum width of 1.8m. Non-motorised ways were defined as hiking trails, including forest, biking and hiking trails with a width less than 1.8m. Formal trails were digitalised manually with the resolution of 1:2 000. Trails were digitalised by creating and editing line features within the shapefile, tracing the existing formal trails on the digital topographic map produced by the Swiss Federal Office of Topography. This resulted in three shapefiles per study area containing all formal trails displayed on the topographic map.

To create a consistent network of trails, informal trail segments, starting or ending on formal trails, were snapped to the formal trail segments, working with the resolution of 1:2 000. Gaps between connected informal trail segments, occurring due to measurement inaccuracies of the GPS device, were snapped together. To ensure a connected trail network, a topology was created and validated in ArcMap. To derive surface information of all trails, the elevation model Swiss Alti 3D with a raster size of 5m x 5m publicised in 2013, was used. With the tool "Add surface information" line features were attributed with spatial information derived from the elevation model, such as minimum, maximum and mean elevation, average slope, and the surface length of each feature. The average slope was obtained by weighing each slope by its length and then calculating the average.

The information collected in the field with GeoODK was joined to the attribute table of the informal trails per study area, equipping each informal trail segment with trail-specific information. This was done by joining the attributes from the .csv table to the informal trail layer of each study area. The joint was based on the name field, containing the trail ID.

3.3.2 Impacts and characterization of informal trail network

To assess the impact of informal trail networks, informal trails were characterized by attributes and, additionally, the total length, total disturbed area and trail density were calculated. To determine the amount of area currently affected by informal trails (lineal extent), the approximate length of each informal trail segment was calculated using GIS analysis techniques. Based on the estimated length, the length of each trail segment was multiplied by the sum of its width and side-effect of trail width. These products were added to calculate the lineal extent occupied by informal trails within the study areas. The total disturbed area was derived by summing the lineal extent and the additional disturbed area, which could have been present, for example due to the creation of a short optional line to avoid muddy sections. Within this thesis, the term "disturbed area" only refers to the directly affected area by informal trail segments and/or TTFs and does not include the area of influence (see Glossary).

Due to the inequality in length of informal trail segments assessed, the average width was standardized within each study area by calculating a weighted arithmetic mean, as follows:

$$Weighted\ arithmetic\ width = \frac{1}{\sum_{i=1}^{n} l_i} \cdot \left(\sum_{i=1}^{n} l_i \cdot w_i \right)$$

Formula 1: Weighted arithmetic width

with n denoting the number of informal trail segments, i denoting an informal trail segment, l_i the length of the segment i and w_i the average width of the segment i.

The user type was normalized per study area by calculating the proportion of each type of use within the study area. This was done by calculating the sum of the trail segments of one user type and dividing this by the total length of the informal trail segments. To derive the proportion of the study area, the weighted user type was multiplied by 100.

$$Normalized\ user\ type\ [\%] = \left(\frac{1}{\sum_{i=1}^{n} l_i} \cdot \sum_{k=r_1}^{r_{ut}} l_k \right) \cdot 100$$

Formula 2: Normalized user type

with n being the number of informal trail segments, i being an informal trail segment, l_i the length of the segment i, ut the user type, with $\{r_1 \ldots r_{ut}\}$ the subset of all segments belonging to ut, k being an informal trail segment of the user type ut and l_k the length of the segment k.

Measures, such as skid marks, signs to prevent usage and forest type were calculated analogously to the normalized user type.

Trail surface and root exposure were calculated using the following formula:

$$Trail\ surface\ [\%] = \frac{1}{A} \cdot \left(\sum_{k=s_1}^{s_t} l_k \cdot w_k \right) \cdot 100$$

Formula 3: Trail surface

with A being the total area (m^2) derived from the study area polygon in GIS, t being the trail surface type, with $\{S_1 \ldots S_t\}$ the subset of all segments belonging to t, k being an informal trail segment of trail surface type t, l_k the length of the segment k and $\mathrm{w_k}$ the width of the segment k. Results are expressed in percentage.

The final excel sheet was converted into a .csv file and imported into R for statistical analysis. Descriptive statistics were used for identifying general characteristics of informal trail segments per study area and for the total impact area.

3.3.3 Impacts of informal mountain bike trails and associated trail technical features

Similar to the informal trails by all user types, the impact of informal trail segments used exclusively by mountain bikers was assessed by deriving the total length and linear extent of the informal mountain bike trail segments. In order to be able to attribute the impacts directly to mountain biking, only those informal trail segments were included, where mountain bike tire marks were the exclusive traces visible at the time of assessment. Informal mountain bike trail density and total disturbed area were calculated. The additional disturbance due to the impact of the construction of trail technical features was added. Descriptive statistics were used for identifying the characteristics of trail technical features encountered.

3.3.4 Comparison of informal trail characteristics among user types

The characteristics of informal trail segments were compared between segments used exclusively by mountain bikers and those used by other user groups. Other user groups may include mountain bikers as well, but do not consist exclusively of mountain bikers. To assess differences in the characteristics of informal trail segments used by mountain bikers exclusively and other user types, the segments were divided into “mountain bikers exclusively” and “used by others.” By considering only informal trail segments used exclusively by mountain bikers, differences can be distinguished more clearly. At the time of the assessment, this category of informal trail segments showed visible traces only in the form of mountain bike tire marks. By comparing these with informal trail segments used by others, differences between the two groups can rather be attributed to mountain biking activity instead of additionally considering multiple-use informal trails (trails, where mountain bike tire marks and other traces, such as boot prints were visible at the time of the assessment). Therefore the differences between the two informal trail types can be easier related to the type of use instead of including all informal trails with mountain bike use. The resultant Excel sheet with all characteristics of the informal trail segments was transferred into R© for statistical analysis. The Shapiro-Wilk-test was used, to test metric attribute data for normal distribution.

The Shapiro-Wilk test was published by Shapiro & Wilk (1965) and tests the null hypothesis (H_0), that a sample x_1- x_n belongs to a normally distributed population (Royston, 1995; Shapiro & Wilk, 1965). On the contrary, the alternative hypothesis (H_1) implies that the population is not normally distributed. If the p-value <0.05, H_0 is rejected.

Due to not normally distributed data, the Wilcoxon-Mann-Whitney test was used to determine if there were any significant differences between characteristics of informal trail segments among the two groups. The Wilcoxon-Mann-Whitney test is a non-parametric statistical test and can be applied to not normally distributed data. The null hypothesis (H_0) states that two samples come from the same population. On the contrary the alternative hypothesis (H_1) implies that one population has higher values than the other. The test compares the determined values of one variable of two samples. Differences were tested for the total area and per study area. For a difference to be significant, p values had to be < 0.05 (Wollschläger, 2014; Yau, 2013).

All statistical analysis was performed using R statistical software Version 3.2.1.

3.3.5 Landscape fragmentation

To further identify impacts of informal trails, calculations of the degree of landscape fragmentation were performed using five landscape fragmentation metrics.

To analyse landscape fragmentation within the study areas by informal trail segments, number of patches (*Npatches*) and the effective mesh size (m_{eff}) were used as landscape fragmentation metrics. Further, the *Weighted Mean Patch Index* (*WMPI*) and the *Largest 5 Patches Index* (*L5PI*) were used as trail-based fragmentation measures. The latter indices have been used in previous studies and have been especially designed as measurements of trail-based fragmentation (Ballantyne et al., 2014b; Leung et al., 2011; Moskal & Halabasky, 2010).

The *effective mesh size* expresses the probability of two randomly chosen points within an area to be found in the same unfragmented region. This is equivalent to the ability of two animals –situated in different areas- finding themselves in the same undivided area. The more barriers exist within a landscape, the lower the probability of connection between the two points and the lower the *effective mesh size*. The *effective mesh size* decreases the more the number of barriers increases within a landscape (Jaeger, 2000).

The *effective mesh* size is calculated as:

$$m_{eff} = (\left(\frac{F_1}{F_g}\right)^2 + \left(\frac{F_2}{F_g}\right)^2 + \left(\frac{F_3}{F_g}\right)^2 + \cdots + \left(\frac{F_n}{F_g}\right)^2) \cdot F_g = \frac{1}{F_g} \cdot \sum_{i=1}^{n} {F_i}^2$$

Formula 4: Effective mesh size (Jaeger et al., 2007)

with n being the number of areas, F_1, F_2 until F_n the surface area of area 1 to area n and with F_g being the total area of the analysed landscape. Sizes of areas are expressed in km^2.

The *Weighted Mean Patch Index* is a modification of the *Mean Patch Size* (*MPS*) described by McGarigal & Marks (1995). The *MPS* does not take the proliferation of informal trails within an area into account. Therefore, a weighting factor was added to adjust the linear extent of informal trails reducing non-fragmented and undisturbed habitat (Leung et al., 2011). The formula is,

$$WMPI = wf \cdot \left(\sum \frac{a_{ij}}{n}\right) \cdot (\frac{1}{10\ 000})$$

Formula 5: Weighted Mean Patch Index (Leung et al., 2011) with n being the total number of patches and wf being the weighting factor, which equals $\left(\sum \frac{a_{ij}}{A}\right)$ with a_{ij} being the area (m^2) of patch ij; A = landscape area (m^2). The results of this metric are represented in hectares, with decreasing values indicating higher fragmentation (range $0 - \infty$).

To avoid misinterpretation, the formula of Leung et al. (2011) (Formula 5) has been modified and the *WMPI* has been calculated according to the following formula (Formula 6):

$$WMPI = wf \cdot \left(\sum_{i=1}^{n} \frac{a_i}{n}\right) \cdot \left(\frac{1}{10\,000}\right)$$

Formula 6: Weighted Mean Patch Index modified

with n being the total number of patches and wf being the weighting factor, which equals $\left(\sum_{i=1}^{n} \frac{a_i}{A}\right)$ with a_i being the area (m^2) of patch i; A = landscape area (m^2). The results of this metric are represented in hectares, with decreasing values indicating higher fragmentation (range $0 - \infty$).

The *Largest 5 Patches Index* (*L5PI*) was adapted from the *Largest Patch Size* (*LPS*) from McGarigal & Marks (1995) (Leung et al., 2011). The *L5PI* is expressed as the sum of the area of the largest five patches divided by the total landscape area, multiplied by a hundred. This index averages the size of the largest five patches rather than using the largest patch and risking over-sensitivity to changes in one single patch. Originally, the index is defined as,

$$L5PI = \sum max_5(a_{ij})/A \cdot 100\%$$

Formula 7: Largest 5 Patches Index (Leung et al., 2011)

with max_i= the largest i patches; a_{ij} = area (m^2) of patch ij, A= area (m^2) of the landscape. Units are expressed in percent and the range spans from 0-100.

In order to avoid misinterpretation, the formula of Leung et al. (2011) has been modified to state the meaning more precisely to the following formula (Formula 8).

The original multiplication by 100% was corrected by multiplying with 100 in order to obtain results expressed in percentage. As stated by the authors “this index is derived from the sum of areas of the five largest patches, divided by total landscape (meadow) area” (Leung et al. 2011).

The modified formula is:

$$L5PI\ [\%] = \frac{1}{A} \cdot \left(\sum_{p=i_1}^{i_5} a_p \right) \cdot 100$$

Formula 8: Largest 5 Patches Index modified

with A = area of the landscape (m^2), i_1 ... i_5 = indices of the five largest patches, p being a patch within A, and a_p being the area (m^2) of patch p. To derive the proportion of the area occupied by the five largest patches within an area the product $\frac{1}{A} \cdot \left(\sum_{p=i_1}^{i_5} a_p \right)$ is multiplied by 100. Results are expressed in percent with decreasing values indicating an increase in degree of fragmentation.

To analyse landscape fragmentation, the study area shapefiles were used as boundary polygons. Within ArcMAP 10.3 formal trails for each study area were buffered within their shapefile containing either forest roads, forest trails or hiking trails. According to the type of formal trails, a linear buffer distance of 3m (forest roads), 2m (forest trails), 1m (hiking trails) was used. Further, each informal trail segment was buffered according to the sum of its average width and width of side-effect. Formal trails of each study areas were merged, using the “Merge” tool in ArcMAP and removed from the boundary polygon. Removal was accomplished by erasing the feature from the boundary polygon. The resultant shapefile represents the study area without formal trails, representing the fragmentation due to formal trails (reference basis).

Similarly, to obtain the fragmented area by informal trails, buffered formal trails and buffered informal trails were merged and removed from the boundary polygon. The resultant buffers represent the total area of the impact associated with trails and informal trail segments. By removing the buffered trails and informal trail segments from the study area shapefile, a shapefile representing the fragmentation by formal and informal trails was created.

In order to gain several separated polygons and to determine the size of each fragmented patch, the “Multipart to singlepart” tool was applied. The resultant attribute table was copied to Excel for further processing. Within Excel, the area of each patch was transformed into km^2 and m_{eff} was calculated for the polygons within a study area, for each study area and for the total study area using Formula 4. The former trail-based indices were calculated according to their formula (Formula 6 and Formula 8).

3.3.5.1 Fragmentation by informal mountain bike trail segments

To determine the fragmentation indices *Npatches*, m_{eff}, *MPS, WMPI* and *L5PI* for informal mountain bike trail segments, informal trail segments used exclusively by mountain bikers were selected within each study area and buffered with the according average width and side-effect of trail width of each trail segment. Buffered segments were merged with the buffered formal trail feature class. The resultant layer was removed from the study area polygon. The result was a polygon without formal and informal mountain bike trail segments. The attribute table was exported into Excel for further calculations. To compare fragmentation indices, indices for the fragmented area by informal trails segments used by other user types were obtained likewise. The fragmentation indices were compared to the reference basis.

3.3.5.2 Fragmentation of roe deer habitat

Roe deer data from the research area “Integrative Ecology” of the research group “Wildlife management” headed by Graf from the ZHAW in Wädenswil were used for this assessment (Ineichen, 2015).The roe deer data represent the home ranges (HR) of each GPS-collared roe deer in study areas located in or close to the Sihlwald. The area occupied by an individual with a 95% probability during a specific period is defined as the home range of an individual (Laver & Kelly, 2008).

Fragmentation of roe deer habitat due to informal trail construction was analysed by assessing which HRs of the twelve selected roe deer were affected by informal trails. By assigning the projected coordinate system CH1903 LV03 to each HR shapefile in ArcMAP Catalog, the size (km^2) of each affected HR was calculated by adding a new field in the attribute table and by using the “calculate geometry” option. Each HR was used as a boundary polygon and the same procedure as mentioned above was fulfilled to obtain the patches for the reference basis habitat (formal trails) and the fragmented-patches (including the informal trails). The attribute tables of the multiple-patch polygon layers were exported into Excel and fragmentation metrics were calculated. The fragmentation metrics of the fragmented habitats by informal trails and the reference basis (fragmentation due to formal trails) of each habitat were compared.

4 Results

4.1 Informal trails in Zuerich's forests

4.1.1 Impacted area and spatial extent

The informal trails mapped during the two-month assessment period in the three study areas have a cumulative total length of 19.7km (Table 4.1). The identified informal trail segments per study area are depicted in Figure 8.2 to Figure 8.4 in the Appendix. The total length of informal trail segments ranges from 2.58km at the Adlisberg to 8.92km in the Sihlwald. Even though, the total length of informal trail segments in the Zuerichberg region comes to 8.17km, proportionally it adds 15.62% to its formal trail counterpart. By contrast, informal trail segments proportionally account for 6.27% in the Sihlwald and 3.80% in the Adlisberg. In total, informal trails contribute an additional 7.49% of trail segments to the formal trail network.

The total disturbed area, including the length, width and side-effect of trail segments and the additional disturbed area, accounts for 0.08% of the total study area, with the Sihlwald contributing 45%, Adlisberg 13% and the Zuerichberg 42% of the disturbed area. The aggregate disturbance area associated with informal trails is numerically highest in the Sihlwald (8 896m^2), whereas the biggest proportion of informal trail based disturbed area is found at the Zuerichberg (0.18%). The share of area disturbed by informal trail segments in the Sihlwald and Adlisberg, accounts for 0.06%. Informal trail density per study area ranges from 493m/km^2 at the Adlisberg to a density of 1855m/km^2 at the Zuerichberg.

Table 4.1: Impacts of informal trails. (The values for the study area size and the percent values were rounded up to two decimal places).

	Sihlwald	Adlisberg	Zuerichberg	Total
Study area size (km^2)	14.19	5.24	4.40	23.84
Total length				
Formal trail network [m]	142 250	68 008	52 268	262 526
Informal trail network [m]	8 924	2 581	8 165	19 671
Proportion study area trailed (informal) [%]	6.27	3.80	15.62	7.49
Total disturbed area				
Numerical [m^2]	8 896	3 245	7 797	19 939
Proportional [%]	0.06	0.06	0.18	0.08
Trail density [m/km^2]				
Formal trail network	10 023	12 976	11 875	11 014
Informal trail network	629	493	1 855	825

The distribution of informal trails segments per study area is displayed in the Appendix Figure 8.2 to Figure 8.4. It has to be pointed out, that the maps are displayed using different scales, due to different sizes of study area.

In the Sihlwald study area most informal trail segments are located outside of the natural forest. Figure 8.8 displays a map of the natural forest, which is georeferenced and overlayed over the map of the identified informal trail segments. High informal trail densities are found in the North East of the study area between the Gattikerweier and the Morschwand region, comprising the forest area between the river Sihl and residential areas. Nearly all remaining informal trail segments are located in the Southwest close to the boundary of the study area. Some informal trail segments follow the border between the cantons Zuerich and Zug.

At the Adlisberg the informal trail density is lower in comparison to the other study areas. Most of the informal trails are located in the West and South East of the study area. No informal trails were identified in the Northern part of the study area. Noticeable is a long trail sloping downhill, consisting mostly of informal trail segments linked with short formal trail stretches.

At the Zuerichberg informal trail segments are clustered close to the boundaries of the study area. Most of them are located between South and West of the study area. Noticeable are the small informal trail networks enclosed by formal structures. Few informal trail segments are found at the northern boundary. Nearly no informal trail segments were identified on the ridge of the Zuerichberg. Remarkable is, that many informal trail segments are aligned to the fall-line.

4.1.2 Informal trail characteristics

Characteristics of the informal trail segments per study area and in total are depicted in Table 4.2. Trail width is categorized in 9 width classes ranging from 0.4m - < 0.6m to ≥2.0m. Trail surface, average slope, root exposure, forest type and preventing usage are displayed in percentages. Because of the possibility of multiple selections of trail surfaces in the field, a total of more than 100% is possible in the category trail surface. The number of informal trail segments partly passing the forest edge is displayed. Trail incision is described with the maximum value, mean and standard deviation. Examples of informal trail segments identified within this study are displayed in Figure 4.1.

Figure 4.1: Examples of informal trails in the study area.

Identified informal trail segments are characterized by a weighted mean width of 0.8m for the Sihlwald and Zuerichberg, 1.0m in the Adlisberg study area and a total weighted mean of 0.9m for all three study areas (Table 4.2). More than two-third of the informal trail segments in the Sihlwald study area have a weighted average width ranging from 0.6m to 0.79m. Within the Adlisberg study area, a little more than one third of informal trails are classified as trails with a width between 0.6m and 0.79m. Approximately 45% of informal trail segments at the Zuerichberg have a weighted average width between 0.6m and 0.79m. Even though most informal trail segments have a width ranging from 0.6m up to and equal to 1.19m, a total of 9.4% of informal trails have a width equal or larger than 2m. Most wide informal trail segments were found in the Adlisberg region with 17.6% in the width classes equal and larger than 2.0m.

In all study areas, informal trails consist predominantly of forest soil, roots and stones. In the Adlisberg and Zuerichberg study area, informal trails have a higher share of loose gravel in comparison to trails in the Sihlwald, with a trail surface proportion of 16.5% (Adlisberg) and 26.7% (Zuerichberg). Solid gravel is found on 19.5% of informal trail segments in the Sihlwald. More than one fifth of informal trail surfaces in the Adlisberg consist of grass, whereas in the other study areas its share is proportionally low.

Table 4.2: Characteristics of informal trail segments.

	Sihlwald	Adlisberg	Zuerichberg	Total
Weighted Average width total [m]	0.8	1	0.8	0.9
Weighted Average width [%]				
0.4m - < 0.6m	5.2	2.2	4.9	4.1
0.6m - 0.79m	68.7	37.6	45.1	50.5
0.8m - 0.99m	11.4	8.7	14.2	11.4
1.0m - 1.19m	5.6	27.1	30.2	21.0
1.2m - 1.39m	0.7	3.5	1.1	1.8
1.4m - 1.59m	0.4	3.2	0.0	1.2
1.6m - 1.79m	0.8	0.0	1.1	0.6
1.8m - 1.99m	0.0	0.0	0.0	0.0
≥ 2.0m	7.3	17.6	3.3	9.4
Trail surface [%]				
Forest soil	97.1	100.0	97.9	98.4
Roots	85.6	69.8	82.3	79.3
Stones	58.9	32.1	32.7	41.2
Gravel loose	5.7	16.5	26.7	16.3
Gravel solid	19.5	1.4	8.7	9.9
Grass	4.6	22.8	0.0	9.1
Sawdust	2.0	0,0	4.2	2.1
Average slope	15.3 ± 9.2	11.7 ± 6.2	11.6 ± 6.2	13.3 ± 7.8
Root exposure [%]	87.2	72.9	84.8	81.6
Forest type [%]				
mixed	92.8	62.1	37.8	64.2
decidious	4.7	37.9	62.2	34.9
coniferous	2.5	0.0	0.0	0.8
Preventing usage [%]	6.7	15.0	9.3	10.3
Partly at forest edge [N°]	16/83	16/38	29/70	61/191
Trail incision [m]				
Maximum	0.50	0.45	0.40	0.50
Mean and standard deviation	0.03+-0.08	0.09+-0.12	0.05+-0.09	0.05+-0.09

The average slope of informal trail segments varies within the study areas, with 15.3% ± 9.2% in the Sihlwald, 11.7% ± 6.2% for the Adlisberg and 11.6% ± 6.2% for the Zuerichberg. Informal trail segments in the three study areas have an average slope of 13.3% ± 7.8%.

Most informal trail segments are associated with root exposure with a total of 81.6%. Root exposure is visible on 87.2% of informal trail segments in the Sihlwald, 84.8% at the Zuerichberg and 72.9% at the Adlisberg.

Predominantly, informal trail segments are found in mixed forest stands with a total of 64.2%. Informal trail segments are especially located in mixed forest stands in the Sihlwald (92.8%). At the Adlisberg, nearly two third of informal trails are located in mixed stands and more than one third are found in deciduous stands. Contrary to the Adlisberg, more than one third of the Zuerichberg's informal trail segments are found in mixed stands, whereas nearly two third are located in deciduous forests.

Management measures to prevent usage of the informal trails account for 10.3% of the informal trail segments; with the Adlisberg having most measures to prevent usage per length of informal trail segments. A total of 61 out of 191 identified informal trail segments lead through areas adjacent to the forest edge, with the highest number at the Zuerichberg (29). Maximum trail incision ranged from 0.4m in the Zuerichberg to 0.5m in the Sihlwald. Even though the maximum trail incision was encountered in the Sihlwald, mean and standard deviation ranged from 0.03m ± 0.08m (Sihlwald) to 0.09m ± 0.12m (Adlisberg).

According to the informal trail assessment (Table 8.1 (I-III)), multiple selections of user type were possible. Therefore the resultant data represents groups of occurring combinations of user types. The user types of the total informal trail network, averaged and weighted by the length of the informal trail segments, are depicted in Figure 4.2. User types of informal trail segments per study area are displayed in Figure 4.3 to Figure 4.5.

Informal trail segments are mainly used by hikers and mountain bikers (36.3%), followed by hikers exclusively (28.3%) and mountain bikers exclusively (22.7%) (Figure 4.2). If multiple-use is considered, 76.9% of all informal trail segments are used by hikers, whereas mountain bikers use 71.2% of the informal trail segments in the total study area. Little more than eight percent of informal trail segments are used by mountain bikers, hikers and forest use, whereas nearly four percent are used by the user group horse riding, mountain biking and hiking. Other user types such as forest use, hiker and horse rider; and hiker and forest use contribute less than one percent to the usage of informal trails within the three study areas.

A predominant use of informal trail segments by mountain bikers and hikers is also visible in the Sihlwald (42.3%) and the Zuerichberg (41.8%) (Figure 4.3 and Figure 4.5). In both study areas, nearly 30% are used exclusively by hikers, followed by 17.0% (Sihlwald) and 22.6% (Zuerichberg) of informal trails segments used exclusively by mountain bikers. If multiple-use is taken into consideration, 83.0% of informal trail segments in the Sihlwald are used by hikers and 69.4% are used by mountain bikers. At the Zuerichberg, 76.6% of informal trail segments are used by hikers and 70.3% are used by mountain bikers. Informal trails used by mountain bikers (considering multiple-use) are depicted per study area in Figure 8.5 to Figure 8.7.

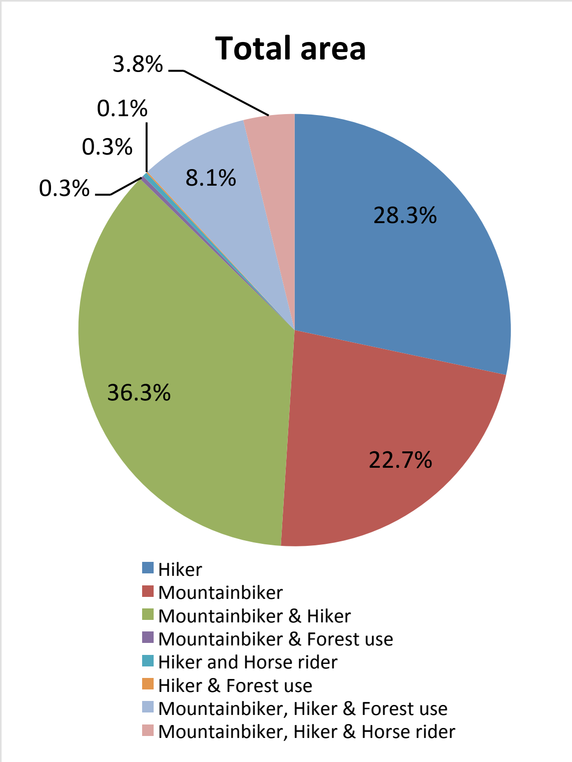

Figure 4.2: User types of informal trail segments.

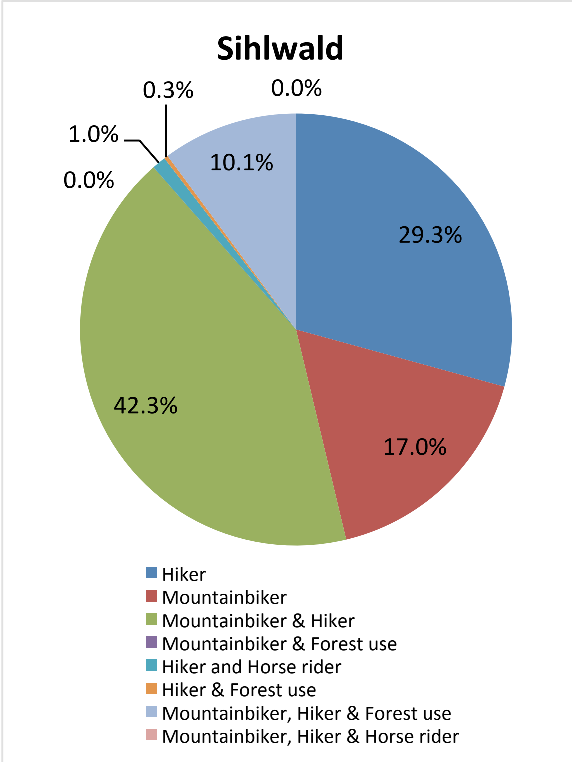

Figure 4.3: User types of informal trail segments in the Sihlwald.

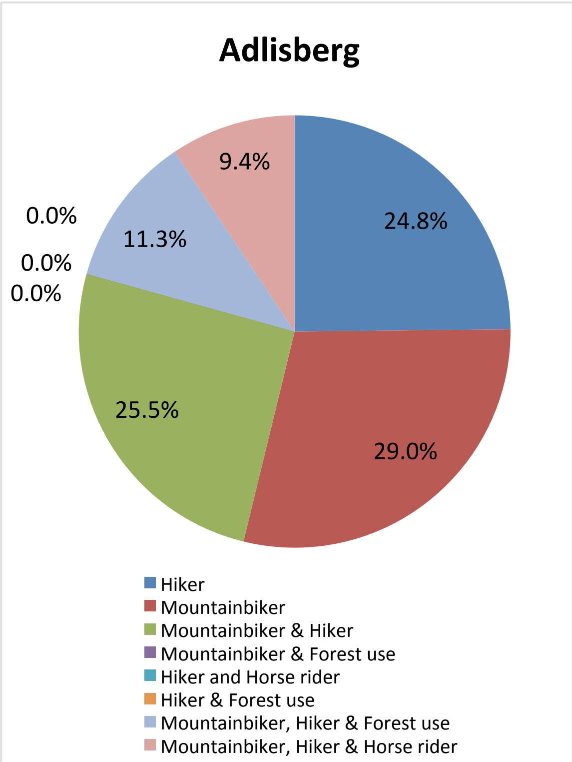

Figure 4.4: User types of informal trail segments at the Adlisberg.

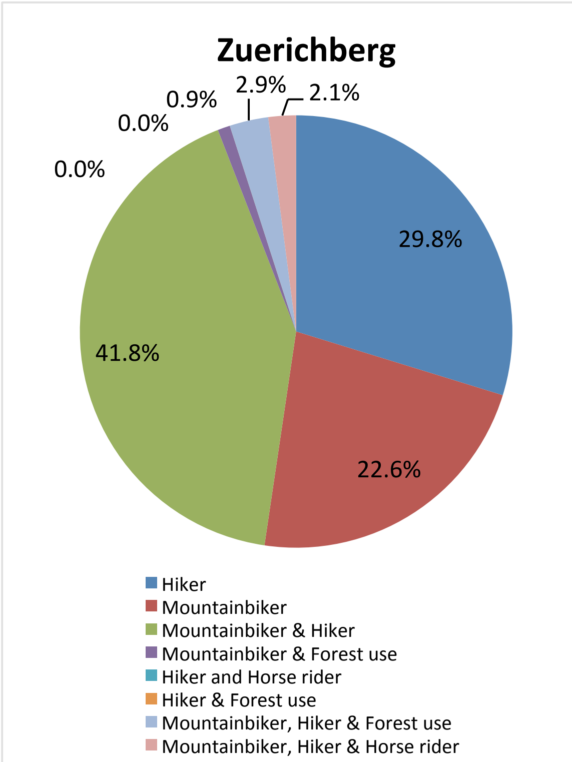

Figure 4.5: User types of informal trail segments at the Zuerichberg.

In the Sihlwald, 10.1% of the informal trail network is used by mountain bikers, hiker and forest use, whereas this user type only contributes to 2.9% of informal trail usage at the Zuerichberg. The user type hikers and forest use, within the Sihlwald study area, use less than one percent of informal trail segments. This user type is not found at the Zuerichberg. A small amount (2.1%) of informal trails at the Zuerichberg is used by mountain bikers, hikers and horse riders. This user type does not occur on identified informal trail segments in the Sihlwald. Hiker and horse riders use one percent of informal trail segments in the Sihlwald, whereas this user type utilizes no informal trail segments at the Zuerichberg. Mountain bikers and forest use at the Zuerichberg use less than one percent of informal trails.

Informal trail segments in the Adlisberg are mainly used exclusively by mountain bikers (29.0%), followed by mountain bikers and hikers (25.5%), hikers exclusively (24.8%) and mountain biker, hiker and forest use (11.3%) (Figure 4.4). If multiple-use is considered, informal trail segments are used to 71.0% by hikers and 75,2% by mountain bikers. The user type mountain biker, hiker and horse rider amounts for 9.4% of informal trail usage. Hiker and forest use; hiker and horse rider; as well as mountain biker and forest use; are user types of informal trail segments which do not occur in this study area.

4.1.3 Landscape fragmentation

4.1.3.1 Informal trail-based fragmentation

Number of patches, median patch size, *WMPI*, *L5PI* and the effective mesh size are used to capture the spatial distribution of informal trails and their contribution to landscape fragmentation. The five fragmentation indices calculated for the formal and informal trail networks are depicted by study area and in total in Table 4.3. Indices are listed for the total of each study area and per polygon within the study area. The column with the results of the total of each study area is indicated by squared brackets. The column with the results per polygon within the study area is indicated by rounded brackets. Changes to the fragmentation by the formal trail network are listed numerically and proportionally. As mentioned in 3.3.5, higher numbers of patches indicate higher fragmentation; whereas smaller numbers in *MPS, WMPI, L5PI* and m_{eff} show higher degree of fragmentation.

The number of patches increases in total and for all study areas, when solely comparing formal trail based fragmentation and fragmentation including all trails (informal and formal) (Table 4.3). Numerically, the number of patches increases from 724 to 870 patches, which accounts for a proportional increase of 20.2%. Even though the Sihlwald has the largest numeric increase (63) in patches, the Zuerichberg has the largest proportional increase (36.6%) in the number of patches. The number of patches in the Sihlwald increases by

20.5%. The Adlisberg shows an increase of 9.1% in patch number, due to informal trail proliferation.

The *MPS* is reduced in all study areas when comparing formal trail fragmentation to fragmentation including all trails. The Sihlwald has the highest numerically decrease (-7 585m^2), followed by the Zuerichberg (-6 947m^2) and the Adlisberg (-1 683m^2). Considering the changes of *MPS* to formal trail based fragmentation proportionally, the Zuerichberg has the biggest decrease proportionally by 27%. The *MPS* in the other study areas decreases by 17.1% (Sihlwald) and by 8.5% for the Adlisberg.

Similarly, the *WMPI* decreases for all study areas, with the largest numeric (-0.7346ha) in the Sihlwald and largest proportional decrease (-27.3%) at the Zuerichberg. The lowest change is visible at the Adlisberg with a reduction of the *WMPI* by 8.6%.

Further, the area comprised by the largest five patches decreases due to informal trail proliferation in all study areas. The highest reduction in *L5PI* from 16.10% to 13.88% is visible at the Zuerichberg (-2.22%). The area comprised by the largest five patches in the Adlisberg decreases by less than 1% within the Adlisberg study region due to informal trails. The lowest change in *L5PI* is visible in the Sihlwald with -0.02%.

Due to the proliferation of informal trails in the study areas, the effective mesh size decreases by 4.6% in total. Informal trail based fragmentation causes a 19.1% reduction of m_{eff} at the Zuerichberg, reducing the effective mesh size numerically by 0.012349km^2. In contrast, the numerical decrease of m_{eff} amounts to -0.00733km^2 in the Sihlwald and -0.004275km^2 at the Adlisberg. Considering the size of the study areas, informal trail segments cause a higher fragmentation in the Adlisberg study region with a decrease of m_{eff} by 8.2% in comparison to 3.1% in the Sihlwald.

Therefore, informal trail based fragmentation is responsible for the creation of 146 patches in the total study area. This is an increase of more than 20%. The effective mesh size decreases by 4.6% in total, with the highest informal trail based fragmentation at the Zuerichberg, with a 19.1% decrease in comparison to the m_{eff} caused by the formal trail network. The *MPS* and the *WMPI* decreased in at the Zuerichberg by more than one quarter, in the Sihlwald by more than 17% and at the Adlisberg by more than 8%. In contrast to other fragmentation indices, the area occupied by the largest five patches only decreased slightly with a maximum decrease of *L5PI* at the Zuerichberg by 2.22%. Considering all fragmentation metrics, informal trail based fragmentation has the highest impact in the Zuerichberg study area, compared to the other study areas. Regarding the number of patches, *MPS* and *WMPI,* the lowest fragmentation is visible at the Adlisberg, whereas the m_{eff} and *L5PI* values changed least in the Sihlwald.

Table 4.3: Landscape fragmentation metrics – quantifying informal trail-based fragmentation. (The values in the row total area were rounded up to two decimal places. The values for the row m_{eff} were rounded to their significant values).

	Sihlwald (1)	Sihlwald (2)	Sihlwald total [01]	Adlisberg (1)	Adlisberg (2)	Adlisberg (3)	Adlisberg total [02]	Zuerichberg [03]	Total [all]
Total area [km²]	3.89	10.30	14.19	3.82	1.16	0.26	5.24	4.40	23.84
Npatches									
formal	149	159	308	196	29	27	252	164	724
informal	179	192	371	211	34	30	275	224	870
Changes numeric	30	33	63	15	5	3	23	60	146
Changes proportional [%]	20.1	20.8	20.5	7.7	17.2	11.1	9.1	36.6	20.2
m_{eff} [km²]									
formal	0.10787	0.28506	0.23651	0.049169	0.065352	0.034578	0.052034	0.064517	0.1642
informal	0.10322	0.27672	0.22918	0.045164	0.059235	0.034558	0.047759	0.052168	0.1566
Changes numeric	-0.00465	-0.00834	-0.00733	-0.004005	-0.006117	-0.000020	-0.004275	-0.012349	-0.0076
Changes proportional [%]	-4.3	-2.9	-3.1	-8.1	-9.4	-0.1	-8.2	-19.1	-4.6
MPS [m²]									
formal	24 739	62 826	44 401	18 544	38 482	9 347	19 853	25 685	
informal	20 534	51 996	36 816	17 206	32 769	8 410	18 170	18 738	
Changes numeric	-4 205	-10 830	-7 585	-1 338	-5 713	-937	-1 683	-6 947	
Changes proportional [%]	-17.0	-17.2	-17.1	-7.2	-14.8	-10.0	-8.5	-27.0	
WMPI [ha]									
formal	2.3446	6.0910	4.2776	1.7647	3.6958	0.9090	1.8952	2.4579	
informal	1.9405	5.0378	3.5430	1.6354	3.3802	0.8176	1.7324	1.7869	
Changes numeric	-0.4041	-1.0532	-0.7346	-0.1293	-0.3156	-0.0914	-0.1628	-0.6710	
Changes proportional [%]	-17.2	-17.3	-17.2	-7.3	-8.5	-10.1	-8.6	-27.3	
L5PI [%]									
formal	26.75	26.76	20.32	14.63	39.73	74.12	10.91	16.10	
informal	26.50	26.76	20.30	13.35	38.73	74.12	9.96	13.88	
Changes proportional	-0.25	0.00	-0.02	-1.28	-1.00	0.00	-0.95	-2.22	

4.1.3.2 Fragmentation of roe deer habitat

As a starting point for further research the present study assessed the impacts of informal trails on wildlife by investigating the degree of fragmentation in roe deer habitats. These impacts were analysed by assessing the effects within the home ranges of twelve roe deer in the Sihlwald study area (Figure 8.1 and Section 3.3.5.2). Due to the small sample size and due to this topic differing from the focus of this thesis, the resultant data is only described briefly.

The home ranges of eight roe deer were affected by informal trails. The results are depicted in Table 4.4. The changes in the number of patches within the home ranges of the roe deer varied from 5% to 40%, with the highest numerically increasing by 5 patches within roe deer habitat. The decrease of m_{eff} ranged from 0.1% to 40.3% due to informal trails. Informal trails created a numerical change in *MPS* ranging from -845m^2 to a reduction of the *MPS* by 7707m^2. Similarly, a reduction of *WMPI* varied from 0.0825ha to 0.7528ha. The area comprised by the largest five patches decreased by 8.90%, as a maximum value. In some roe deer habitats the *L5PI* did not change as a result of informal trail proliferation. Even though the effects of informal trail based fragmentation to roe deer habitat varied, some changes like an increase in patch number from 12 to 17 patches were large when regarding habitat size. A decrease of mean patch and weighted mean patch index by up to 30%, might have effects on roe deer activity.

Table 4.4: Informal trail-based fragmentation of roe deer habitat. (The values in the row "total area" were rounded up to two decimal places. The values in the row m_{eff} were rounded to their significant values. Calculations were conducted by using the exact (not rounded) values).

	HR RE01	HR RE02	HR RE07	HR RE10	HR RE11	HR RE12	HR RE13	HR RE15
Total area [km^2]	0.29	0.73	0.29	0.35	0.54	0.34	0.55	0.32
Npatches								
formal	13	20	30	19	25	19	18	12
informal	15	21	33	21	30	24	23	17
Changes numeric	2	1	3	2	5	5	5	5
Changes proportional [%]	15.4	5.0	10.0	10.5	20.0	26.3	27.8	40.0
m_{eff} [km^2]								
formal	0.0536	0.0907	0.0356	0.12349	0.13741	0.0272	0.0668	0.0541
informal	0.0368	0.0906	0.0348	0.12184	0.08206	0.0258	0.0662	0.0484
Changes numeric	-0.0168	-0.0001	-0.0008	-0.00165	-0.05535	-0.0014	-0.0006	-0.0057
Changes proportional [%]	-31.3	-0.1	-2.2	-1.3	-40.3	-5.0	-0.9	-10.5
MPS [m^2]								
formal	21082	35536	9117	18059	20625	17009	29169	25967
informal	18146	33828	8272	16318	17154	13425	22785	18260
Changes numeric	-2936	-1708	-845	-1741	-3471	-3584	-6384	-7707
Changes proportional [%]	-13.9	-4.8	-9.3	-9.6	-16.8	-21.1	-21.9	-29.7
WMPI [ha]								
formal	2.0137	3.4394	0.8726	1.7515	1.9819	1.5987	2.8049	2.5133
informal	1.7214	3.2724	0.7901	1.5805	1.6452	1.2580	2.1870	1.7605
Changes numeric	-0.2923	-0.1670	-0.0825	-0.1710	-0.3367	-0.3407	-0.6179	-0.7528
Changes proportional [%]	-14.5	-4.9	-9.4	-9.8	-17.0	-21.3	-22.0	-30.0
L5PI [%]								
formal	83.28	69.16	66.15	83.48	76.32	51.98	68.34	80.89
informal	74.47	69.14	63.96	83.07	69.35	50.40	68.33	71.99
Changes proportional	-8.81	-0.02	-2.19	-0.41	-6.97	-1.58	0.01	-8.90

4.2 Informal mountain bike trail segments

4.2.1 Impacted area and spatial extent

Even though mountain bikers use a total of 71.2% of all informal trail segments within the study area, the impact caused by mountain biking on informal trail segments is only assessed by considering those trail segments where mountain bike tire marks were the only visible traces at the time of the assessment (see 3.3.3). Informal mountain bike trail segments used exclusively by mountain bikers and trail technical features are depicted by study area in Figure 4.6 to Figure 4.8. In order to better depict informal trail networks and TTFs, it should be noted that the maps displayed are represented at different scales. According to the variability of the study area sizes, the Sihlwald is displayed at a scale of 1:30 000, the Adlisberg at 1:20 000 and the Zuerichberg at 1:15 000.

Informal mountain bike trail segments in the three study areas add up to a total length of 4 109m (Table 4.5). The cumulative length of the informal mountain bike trail segments varies between study areas, with the Zuerichberg having a total length 1 843m, followed by the Sihlwald with 1 517m and the Adlisberg with 748m. To the existing formal trail network, informal mountain bike trail segments contribute 3.53% (Zuerichberg), 1.1% (Adlisberg) and 1.09% (Sihlwald) of additive length. Within the study areas, informal mountain bike trail segments account for 28.98% at the Adlisberg, 22.58% at the Zuerichberg and for 17.01% in the Sihlwald of the informal trail network.

The total disturbed area, due to the construction of informal mountain bike trail segments, accounts for 4 028m^2, which represents slightly more than one fifth of the total area disturbed by informal trail segments. Considering the size of the study area, the area disturbed by informal mountain bike trail segments accounts for 0.01% (Sihlwald), 0.02% (Adlisberg) and 0.04% (Zuerichberg), summing up to a total of 0.02% of disturbance by informal mountain bike trail segments.

The informal trail density of mountain bike trail segments ranges from 107m/km^2 in the Sihlwald to a trail density of 419m/km^2 at the Zuerichberg. Mountain bike skid marks were recorded on nearly 16% of the informal trail segments, with the highest occurrence in the Sihlwald (25.7%).

Table 4.5: Impacts of informal mountain bike trails and associated trail technical features. (The values for the study area size were rounded up to two decimal places).

	Sihlwald	**Adlisberg**	**Zuerichberg**	**Total**
Study area size [km^2]	14.19	5.24	4.40	23.84
Length				
Formal [m]	142 250	68 008	52 268	262 526
Informal total [m]	8 924	2 581	8 165	19 671
Informal mtb [m]	1 517	748	1 843	4 109
Additive length mtb [%]	1.07	1.10	3.53	1.57
Total area of disturbance				
Informal total [m^2]	8 896	3 245	7 797	19 939
Informal mtb [m^2]	1 413	989	1 626	4 028
Mtb disturbance [%]	0.01	0.02	0.04	0.02
Disturbance TTF [m^2]	211	52	116	379
Disturbance TTF [%]	13.02	5.00	6.64	8.60
Total disturbed area by mtb [m^2]	1 624	1 041	1 741	4 407
Total disturbance by mtb [%]	0.01	0.02	0.04	0.02
Disturbance density				
Formal [m/km^2]	10 023	12 976	11 875	11 014
Informal total [m/km^2]	629	493	1 855	825
Informal mtb [m/km^2]	107	143	419	172
Skid marks [%]				
	25.72	10.86	10.75	15.78

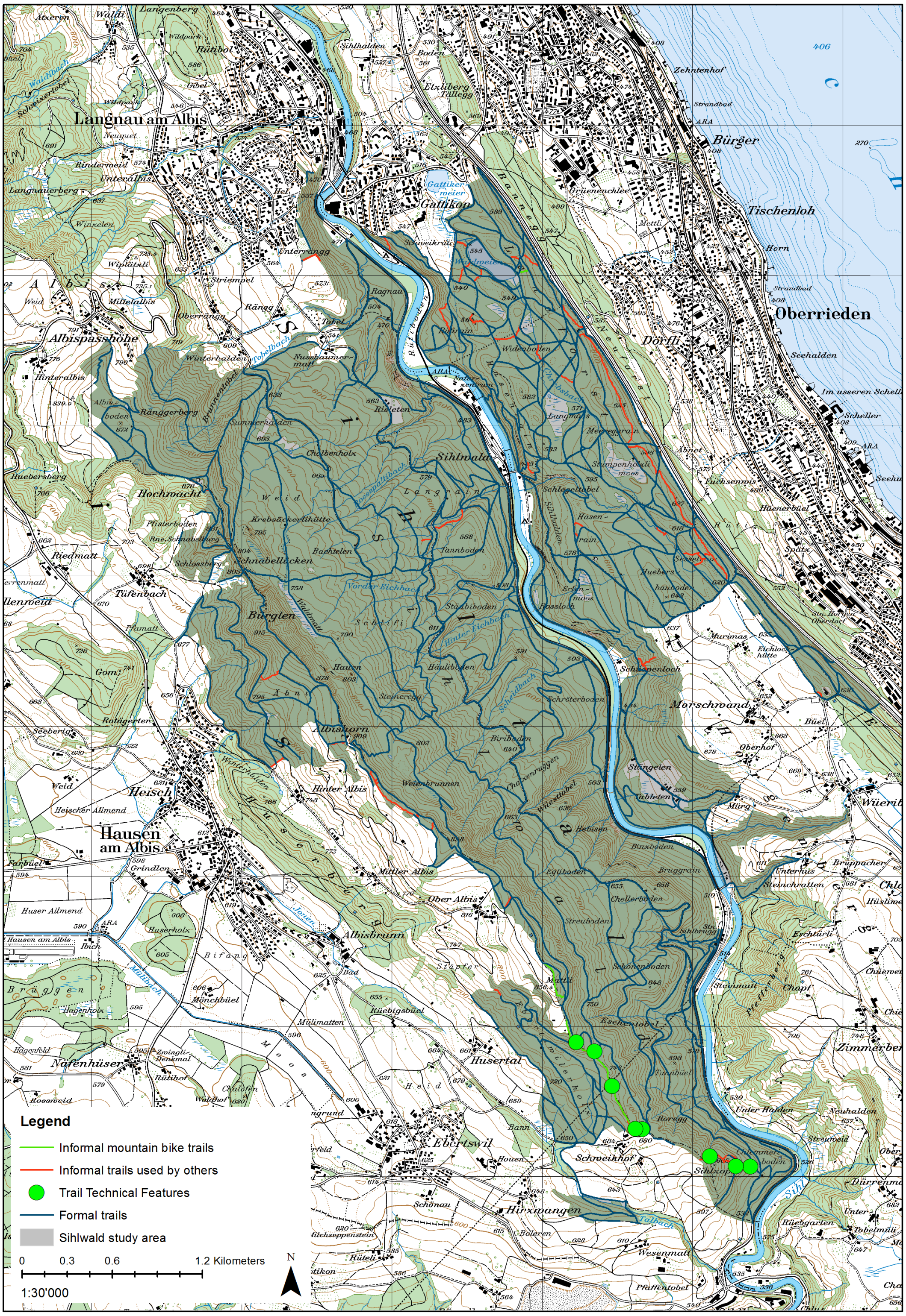

Figure 4.6: Informal mountain bike segments and trail technical features in the Sihlwald.

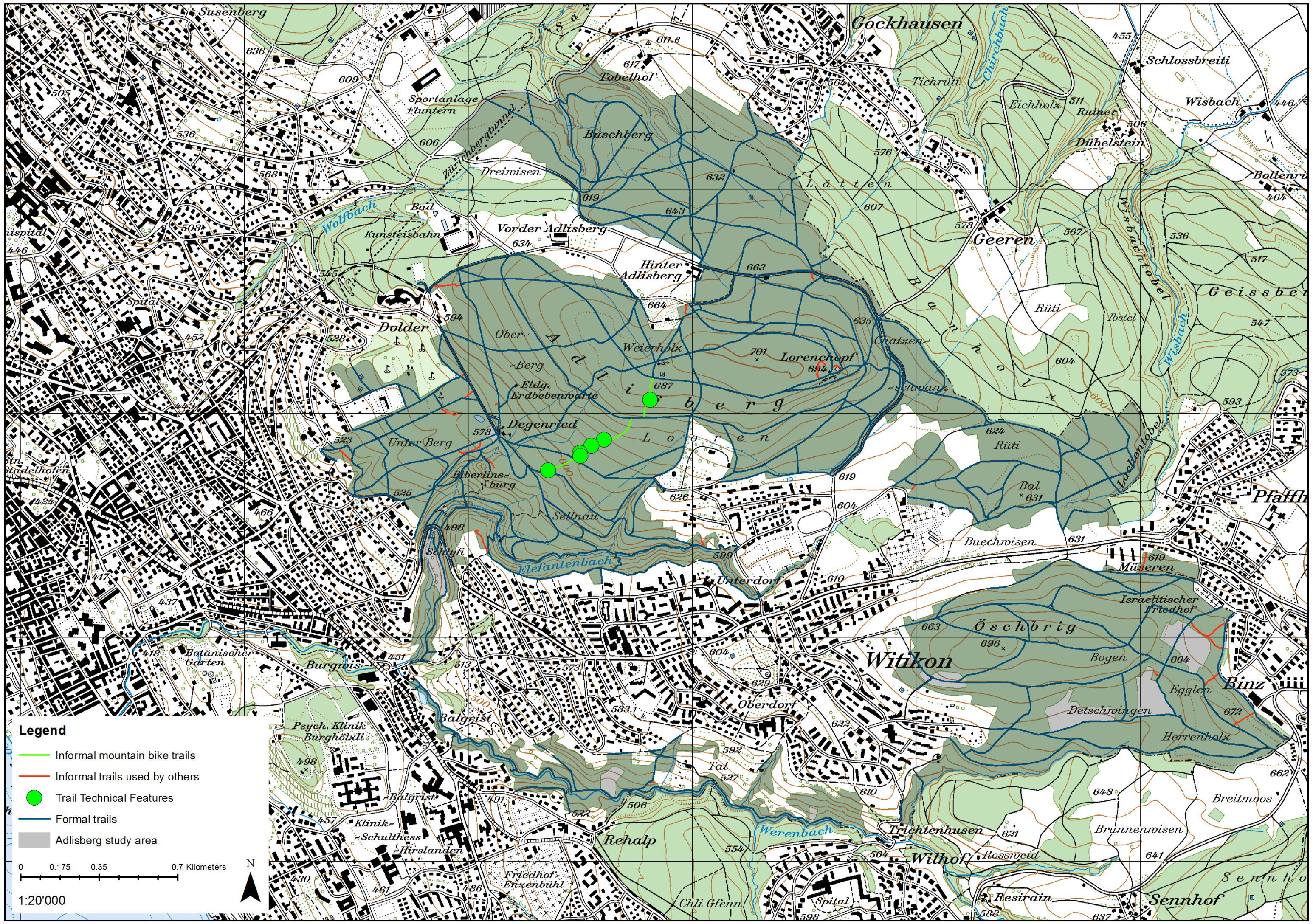

Figure 4.7:Informal mountain bike segments and trail technical features at the Adlisberg.

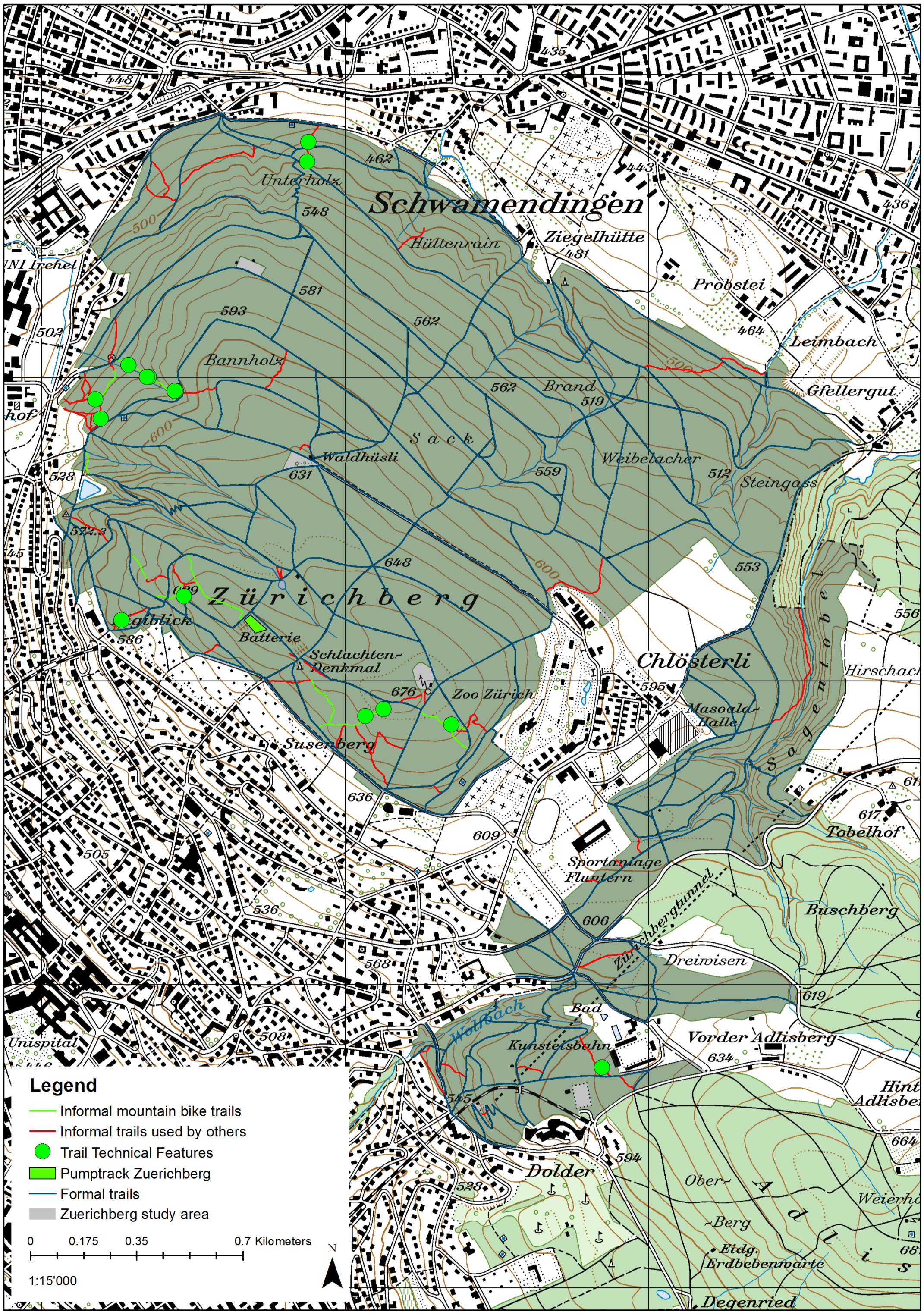

Figure 4.8: Informal mountain bike segments and trail technical features at the Zuerichberg.

4.2.2 Trail technical features

Figure 4.9: Examples of identified Trail Technical Features within the study area.

Figure 4.6 to Figure 4.8 depict the informal trail segments per study area. Displayed are the informal trail segments used exclusively by mountain bikers and informal trail segments used by others. Trail technical features are depictured as points. Examples of identified TTFs within the study areas are displayed in Figure 4.9.

The informal trail network in the three study areas includes 29 TTFs. Most TTFs are found in the Zuerichberg study area (15). In total, nearly two thirds are located on informal mountain bike trail segments. The remaining TTFs were found on informal trail segments shared by mountain bikers and other user types.

According to the TTF group, most of the features were aerial. The most common type of trail technical feature, according to the riding opportunity, was jumps (Table 8.3). Other types of feature in the study areas were logs, drop-offs, berms, bridges, ladder bridges, log steps and others. More than half of the TTFs were enhanced natural and just about 3/4 of the features were located on the informal trails themselves.

The size of structures was variable with an average dimension of 1.78m in length, 1.09m in width and 0.38m in height. Some features were much bigger, with the longest of 5.6m, widest of 2.17m and highest of 1.8m.

Most of the features were constructed by incorporating local vegetation (83%) and soil (76%). Local vegetation included mostly logs as a construction material. Whereas imported timber was only used for the construction of two features.

The condition varied from more than half of the features being in good condition to nearly 1/3 being in poor condition. The safety of the features was mostly rated as moderate. Considering the presence of fall zones and optional lines, only at one TTF site, a fall zone was present, whereas more than 50% of the features were associated with optional lines. At the site of two structures, signs of severe measurements to prevent usage were visible in forms of glass splinters at the entrance of the TTF and a spike sticking out on the top of a TTF.

When considering the feature by itself, the disturbed area ranged from 0.08m^2 up to 5.6m^2, with a mean of 2.0m^2. By adding the disturbed area caused by the construction of trail technical features, such as the area of bare soil, area without understory and optional lines, a different picture is represented, with total disturbed areas, ranging from 0.08m^2 of up to 125m^2, with a mean of 13.1m^2. More than 1/3 of the features were associated with root exposure; six features included the removal of native vegetation, whereas none of the features was associated with rubbish. The total disturbed area caused by TTFs comes to 379m^2, contributing to 8.6% of total disturbed area caused by off-trail mountain biking. Additional impact caused by TTFs accounts for 13.02% in the Sihlwald, 6.64% at the Zuerichberg and 5% at the Adlisberg (Table 4.5). Including the contribution of TTFs to the disturbance area caused by off-trail mountain biking, a total of 4 407m^2 are affected by informal mountain bike trails and associated TTFs. Therefore, 22.10% of total disturbed area of informal trail segments originates from mountain biking off-trail.

4.2.3 Comparison of characteristics among informal trail segments used exclusively by mountain bikers and informal trail segments used by other user groups

In order to examine differences in the characteristics of informal trail segments they were divided into informal trail segments used exclusively by mountain bikers and those used by others. Differences in trail characteristics among these two categories were tested for the following variables: average slope, width of trail average, side-effects of trail width, maximum trail incision, total disturbed area and root exposure. Table 4.6 displays the results of the Wilcoxon-Mann-Whitney test. For tested variables, where significant differences in total or within the study areas occurred, mean and standard deviation of the measure are depicted. Significant differences ($p<0.05$) are highlighted in bold. For tested variables with no significant difference, only the p value is presented. Informal mountain bike trail segments accounted for a total of 31 segments (Sihlwald n=11, Adlisberg n=8, Zuerichberg n=12). Informal segments used by others accounted for a total of 159 segments (Sihlwald n= 72, Adlisberg n=29, Zuerichberg n=58).

Results show significant differences between informal trail segments used exclusively by mountain bikers (n=31) and informal trail segments used by other user types (n=159). The variables average slope, side-effect of trail width and maximum trail incision differ significantly among the two groups. In one study area the average trail width also differed significantly between the two groups. There were no significant differences in total disturbed area and root exposure among informal mountain bike trail segments and other informal trail segments.

The average slope of informal mountain bike trail segments was significantly steeper in comparison to other informal trail segments (p=0.003). Informal mountain bike trail segments had a mean of 16.9% ± 7.6%, whereas other informal trail segments had a mean of 12.6% ± 7.7% (Table 4.6).

Figure 4.10 shows boxplots for the average slope depicted per study area. Boxplots representing the distribution of informal mountain bike trail segments are coloured in orange, whereas boxplots in blue represent the distribution for other informal trail segments. The Figure shows that informal mountain bike trail segments in all three study areas were steeper in comparison to the average slope of other informal trail segments. The average slope between informal mountain bike trail segments and other informal trail segments differed significantly in the Sihlwald (p=0.002) and the Adlisberg (p=0.029) (Table 4.6). The highest significant difference occurred in the Sihlwald with a mean of 22.6% ± 7.1% on informal mountain bike trail segments and 14.3% ± 9.0% for other informal segments (Table 4.6). The average slope for informal mountain bike trail segments at the Adlisberg ranges from a minimum of 10.7% to a maximum of 19.9%. 50% of informal mountain bike trail segments at the Adlisberg have the attribute of an average slope between 13.2% and 17.8%. However, 50% of the informal trail segments used by others have an average slope varying between 6.1% and 13.9%, with a median of 8.7% (Figure 4.10).

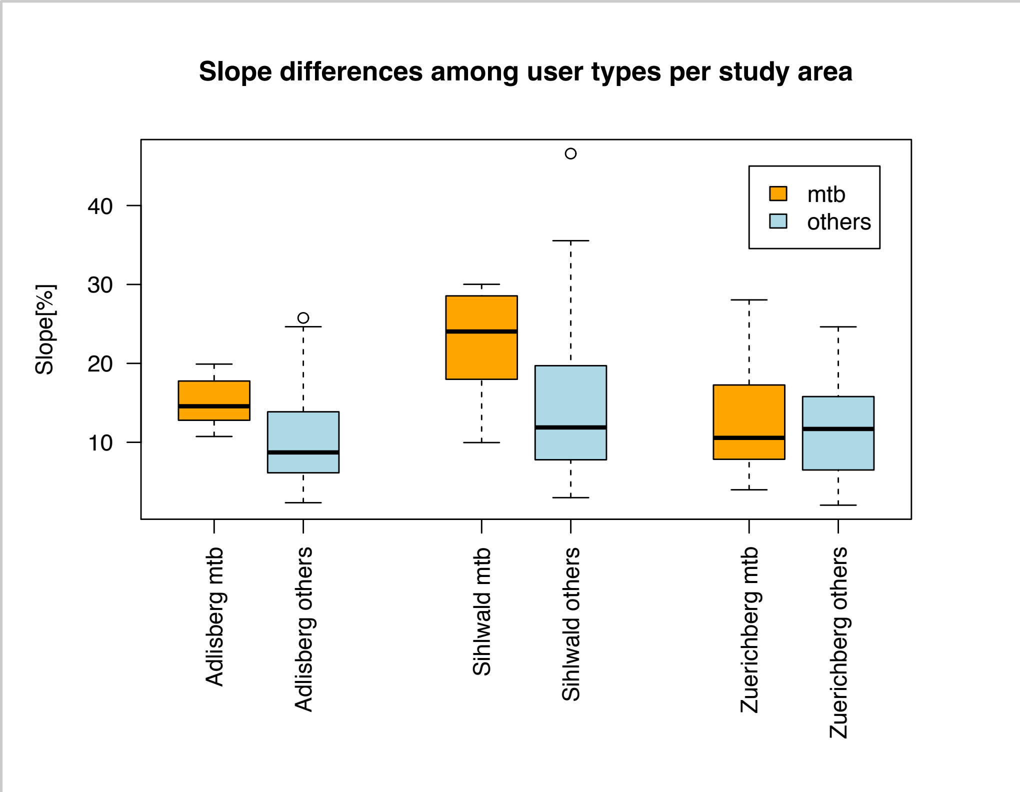

Figure 4.10: Differences of slope among user types per study area.

Even though the maximum average slope is found on other informal trail segments in the Adlisberg, 2/3 of the informal segments used by others have a slope with less than 13.9%. In the Sihlwald half of the informal mountain bike trail segments have an average slope variation from 18% to 29%, with a median of 24%. Two third of the informal trail segments used by others have a slope with less than 20%. The median for other informal trail segments in the Sihlwald is 11.9%. In contrast to the Sihlwald and the Adlisberg, the average slope at the Zuerichberg between the two user groups is quite similar. Half of the informal mountain bike trail segments have an average slope varying between 8% and 17%, with a median of 10.6%. Fifty percent of the informal trail segments used by other users have an average slope between 6.5% and 16% (Figure 4.10).

There was a significant difference in average trail width between the two groups in the Zuerichberg study area (p=0.036) (Table 4.6). In this area, informal mountain bike trail segments were characterised by a smaller average width (0.7m ± 0.1m), in contrast to informal trail segments used by other user types (0.9m ± 0.4m). Even though average trail width of informal mountain bike trail segments tend to be narrower in total, average trail width did not differ significantly between the two groups.

When data on the side-effect of trail were compared, there were significant differences among informal trail segments used exclusively by mountain bikers and other informal trail segments (p=0.001). Informal mountain bike trail segments had a higher side-effect of trail than other informal trail segments. In the Adlisberg and the Zuerichberg differences were significant, whereas the side-effect of trail in the Sihlwald of informal mountain bike trail segments and other informal segments was similar and did not differ.

Table 4.6: Differences of trail characteristics among informal trail segments used exclusively by mountain bikers and those used by others. (The results of the Wilcoxon-Mann-Whitney test are depicted with significant differences indicated in bold. Mean and standard deviation are depicted for characteristics were significant differences occurred. The p-values were rounded up to three decimal places).

	Sihlwald	Adlisberg	Zuerichberg	Total
Average slope [%]				
Mountain bikers	22.6 ± 7.1	15.1 ± 3.2	12.8 ± 7.3	16.9 ± 7.6
Others	14.3 ± 9.0	10.8 ± 6.5	11.4 ± 6.0	12.6 ± 7.7
p value	**0.002**	**0.029**	0.680	**0.003**
Width of trail average [m]				
Mountain bikers	0.8 ± 0.5	1.1 ± 0.6	0.7 ± 0.1	0.8 ± 0.4
Others	0.9 ± 0.6	1.0 ± 0.5	0.9 ± 0.4	0.9 ± 0.5
p value	0.750	0.750	**0.036**	0.435
Sideeffect of trail width [m]				
Mountain bikers	0.15 ± 0.23	0.28 ± 0.11	0.20 ± 0.19	0.20 ± 0.19
Others	0.15 ± 0.2	0.14 ± 0.22	0.10 ± 0.23	0.13 ± 0.22
p value	0.788	**0.005**	**0.001**	**0.001**
Maximum trail incision [m]				
Mountain bikers	0.06 ± 0.10	0.27 ± 0.10	0.12 ± 0.12	0.14 ± 0.14
Others	0.03 ± 0.08	0.03 ± 0.06	0.04 ± 0.07	0.03 ± 0.07
p value	0.714	**0.000**	**0.002**	**0.000**
Total disturbed area [m²]				
p value	0.963	0.283	0.210	0.138
Root exposure [m²]				
p value	0.618	0.066	0.158	0.112

There were significant differences in maximum trail incision between the two groups (p=0.000) (Table 4.6). Maximum trail incision was higher on informal mountain bike trail segments with a mean and standard deviation of 0.14m ± 0.14m, in comparison to 0.03m ± 0.07m for other informal trail segments. The boxplots in Figure 4.11 depict the distribution of maximum trail incision per study area. The distribution of the maximum trail incision for informal mountain bike trail segments is coloured in orange, whereas for other informal trail segments it is displayed in blue.

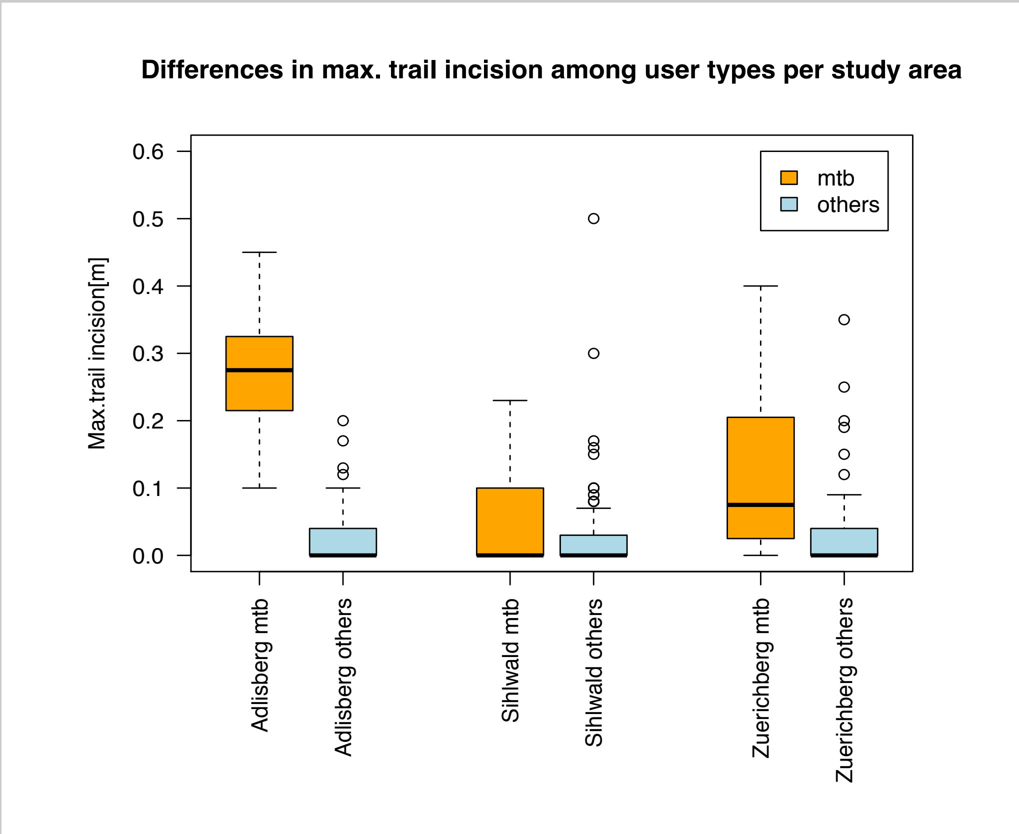

Figure 4.11: Differences in maximum trail incision among user types.

Maximum trail incision differed significantly between the two user groups in the Adlisberg (p=0.000) and the Zuerichberg study area (p=0.002) (Table 4.6). However, maximum trail incision did not differ significantly in the Sihlwald. Half of the informal mountain bike trail segments in the Adlisberg had a maximum trail incision, between 0.22cm and 0.31cm, with a median of 0.28cm. Two thirds of other informal trail segments, however, had the maximum trail incision lower than 0.04cm. In the Zuerichberg, the value of maximum trail incision for half of the informal mountain bike trail segments lay between 0.03cm and 0.20cm, with a median of 0.08cm. However, half of the other informal trail segments had their maximum trail incision between 0cm and 0.04cm, with a median of 0cm and a mean of 0.04cm (Figure 4.11).

4.2.4 Fragmentation by informal trail segments used exclusively by mountain bikers

The fragmentation metrics presented in Table 4.7 (I + II) address the fragmentation effects of informal trail segments used exclusively by mountain bikers in comparison to the formal trail network and to other informal trail segments. The fragmentation metrics are depicted for formal trails, informal mountain bike trail segments and other informal trail segments. Fragmentation metrics are listed for each study area polygon (indicated by the number in rounded brackets) and for the total of each study area (indicated by the number in squared brackets). Additionally, number of patches and m_{eff} are displayed for the study area in total. Changes to the fragmentation by the formal trail network are listed numerically and proportionally for informal mountain bike and other informal trail segments.

Focussing on the fragmentation caused by informal trail segments used exclusively by mountain bikers, differences between the degree of fragmentation of informal mountain biking trail segments and other informal trail segments are visible. The degree of fragmentation varies not only between informal mountain bike trails and other informal trails, but differs among the study areas.

In total, informal mountain bike trail segments increase the number of patches from 724 patches to 744 patches (proportional increase of 2.8%). In contrast, other informal trail segments increase the patch number by 117, which is a proportional increase by 16.2%. Within the study areas, informal mountain bike segments increase the number of patches numerically by nine in the Sihlwald, eight in the Zuerichberg and three patches in the Adlisberg. Considering the varying sizes of the study areas, the highest proportional increase in patch number, due to informal mountain bike trail segments, in comparison to the patch number created by formal trail networks, is visible at the Zuerichberg with a total of 4.9%. The Sihlwald has an increase of 2.9%, whereas the Adlisberg has an increase of 1.2% caused by informal mountain bike trail segments. In contrast, the proportional change in number of patches due to other informal trail segments lies by 26.8% in the Zuerichberg study area, 17.2% in the Sihlwald and by 7.9% in the Adlisberg. The proportional increase in patch number is by 21.9% in the Zuerichberg, 14.3% in the Sihlwald and by 6.7% in the Adlisberg, higher for other informal trail segments in comparison to informal mountain bike trail segments.

All study areas show a bigger decrease in *MPS* for other informal trail segments in comparison to informal mountain bike trail segments. The *MPS* decreases proportionally in the Zuerichberg with 21.4%, followed by the Sihlwald with 14.8% and the Adlisberg with 7.4% for other informal trail segments in comparison to the formal trail network. In contrast, the *MPS* decreases by 4.7% (Zuerichberg), 2.9% (Sihlwald) and 1.2% (Adlisberg) for informal mountain bike trail segments. The decrease in *MPS* for other informal trail segments accounts for 6558m^2 in Sihlwald, 5490m^2 in the Zuerichberg and 1475m^2 in the Adlisberg. The numerical decrease of the *MPS* for informal mountain bike trail segments ranges from 241m^2 (Adlisberg) to 1269m^2 (Sihlwald). Comparing changes in the *MPS* resulting from informal mountain bike trail segments and other informal trails segments, other informal trail segments account for a higher decrease with 16.7% (Zuerichberg), 11.9% (Sihlwald) and 6.2% (Adlisberg).

When comparing the *WMPI* caused by formal trail fragmentation, the *WMPI* due to the fragmentation of informal mountain bike trail segments showed the biggest decrease at the Zuerichberg (4.8%), followed by the Sihlwald (2.9%) and the Adlisberg (1.3%). Due to the fragmentation by other informal trail segments, the *WMPI* decreased by 21.6% in the Zuerichberg, 14.8% in the Sihlwald and 7.5% in the Adlisberg in comparison to the *WMPI* caused by formal trail fragmentation. Similar to the *MPS*, the difference of *WMPI* between the fragmentation due to informal mountain bike trail segments and other informal trail segments is proportionally highest for the Zuerichberg with 16.8%, followed by the Sihlwald 11.9% and the Adlisberg with 6.2%.

The fragmentation indices *L5PI* and m_{eff} show a higher decrease for the informal mountain bike trail segments at the Adlisberg. The *L5PI* decreases from 10.91% to 10.09% for informal mountain bike trail segments, whereas it decreases only by 0.11% for other informal segments. The *L5PI* shows no change in the Sihlwald and a change of 0.52% at the Zuerichberg due to informal mountain bike trail segments. On the contrary small changes in the *L5PI* were encountered for other informal trail segments in the Sihlwald (-0.02%) and a change of -1.51% at the Zuerichberg. The proportional difference between other informal segments and informal mountain bike trail segments lies by 0.02% in the Sihlwald, 0.71% at the Adlisberg and 0.99% at the Zuerichberg.

Similar to the behaviour of the *L5PI*, the m_{eff} decreases more strongly in the Sihlwald and the Zuerichberg for other informal trail segments, whereas the m_{eff} has a higher decrease in the Adlisberg area for informal mountain bike trail segments in comparison to other informal trail segments. The proportional decrease of m_{eff} to the m_{eff} by formal trails accounts for -5.3% in the Adlisberg and Zuerichberg and for -0.2% in the Sihlwald for informal mountain bike trail segments, whereas the m_{eff} decreases by 14.5% in the Zuerichberg and 2.9% in the Adlisberg and Sihlwald. However, the effective mesh size changes by -2.9% in the Sihlwald and Adlisberg and by -14.5% at the Zuerichberg in comparison to the m_{eff} of the formal trail network within the study areas. Differences of other informal trail segments to informal mountain bike trail segments account for 9.2% (Zuerichberg), 2.7% (Sihlwald) and for 2.4% (Adlisberg). According to the m_{eff} , other informal trail based fragmentation is higher in the Sihlwald and the Zuerichberg, whereas the fragmentation in the Adlisberg is higher for informal mountain bike trail segments.

Fragmentation effects of informal mountain bike trail segments accounted for an increase of patch number by 2.8% in the total study area. The decrease of *MPS* ranged from 1.2% to

4.7% in the three study areas. Similar the change of *WMPI* ranged from -4.8% to -1.3%. The area comprised by the largest five patches decreased with a maximum of 0.82% in the Adlisberg study area.

In comparison to fragmentation effects caused by other informal trail segments, fragmentation due to informal mountain bike trail segments was lower regarding the fragmentation metrics number of patches, *MPS* and *WMPI*. According to the *effective mesh size* and the *Largest Five Patch Index* a higher level of fragmentation was visible for informal mountain bike trails at the Adlisberg. In contrast, regarding these two indices, fragmentation had a higher level in the Sihlwald and at the Zuerichberg for other informal trail segments.

Table 4.7 (I): Landscape fragmentation by informal trail segments used exclusively by mountain bikers. (The values in the row "total area" were rounded up to two decimal places. Calculations were conducted by using the exact (not rounded) values. The values in the row „m_{eff}" were rounded to their significant values).

	Sihlwald (1)	Sihlwald (2)	Sihlwald total [01]	Adlisberg (1)	Adlisberg (2)	Adlisberg (3)	Adlisberg total [02]	Zuerichberg (1)	Total [all]
Total area [km²]	3.89	10.30	14.19	3.82	1.16	0.26	5.24	4.40	23.84
Npatches									
formal	149	159	308	196	29	27	252	164	724
informal mtb	150	167	317	199	29	27	255	172	744
informal others	178	183	361	208	34	30	272	208	841
Changes mtb numeric	1	8	9	3	0	0	3	8	20
Changes others numeric	29	24	53	12	5	3	20	44	117
Changes mtb proportional [%]	0.7	5.0	2.9	1.5	0.0	0.0	1.2	4.9	2.8
Changes others proportional [%]	19.5	15.1	17.2	6.1	17.2	11.1	7.9	26.8	16.2
m_{eff} [km²]									
formal	0.10787	0.28506	0.23651	0.049169	0.065352	0.034578	0.052034	0.06452	0.16418
informal mtb	0.10784	0.28431	0.23595	0.045407	0.065352	0.034578	0.049293	0.06111	0.16262
informal others	0.10326	0.27737	0.22965	0.048926	0.059235	0.034558	0.050500	0.05513	0.15803
Changes mtb numeric	-0.00003	-0.00075	-0.00056	-0.003762	0.000000	0.000000	-0.002741	-0.00341	-0.00156
Changes others numeric	-0.00461	-0.00769	-0.00686	-0.000243	-0.006117	-0.000020	-0.001534	-0.00939	-0.00615
Changes mtb proportional [%]	0.0	-0.3	-0.2	-7.7	0.0	0.0	-5.3	-5.3	-1.0
Changes others proportional [%]	-4.3	-2.7	-2.9	-0.5	-9.4	-0.1	-2.9	-14.5	-3.7
MPS [m²]									
formal	24 739	62 826	44 401	18 544	38 482	9 347	19 853	25 685	
informal mtb	24 573	59 802	43 132	18 255	38 482	9 347	19 612	24 472	
informal others	20 649	54 566	37 843	17 463	32 769	8 410	18 378	20 195	
Changes mtb numeric	-166	-3 024	-1 269	-289	0	0	-241	-1 213	
Changes others numeric	-4 090	-8 260	-6 558	-1 081	-5 713	-937	-1 475	-5 490	
Changes mtb proportional [%]	-0.7	-4.8	-2.9	-1.6	0.0	0.0	-1.2	-4.7	
Changes others proportional [%]	-16.5	-13.1	-14.8	-5.8	-14.8	-10.0	-7.4	-21.4	

Table 4.7 (II): Landscape fragmentation by informal trail segments used exclusively by mountain bikers.

	Sihlwald (1)	Sihlwald (2)	Sihlwald total [01]	Adlisberg (1)	Adlisberg (2)	Adlisberg (3)	Adlisberg total [02]	Zuerichberg (1)	Total [all]
WMPI [ha]									
formal	2.3446	6.0910	4.2776	1.7647	3.6958	0.9090	1.8952	2.4579	
informal mtb	2.3289	5.7964	4.1552	1.7363	3.6958	0.9090	1.8715	2.3401	
informal others	1.9515	5.2882	3.6425	1.6608	3.1419	0.8176	1.7528	1.9272	
Changes mtb numeric	-0.0157	-0.2946	-0.1224	-0.0284	0.0000	0.0000	-0.0237	-0.1178	
Changes others numeric	-0.3931	-0.8028	-0.6351	-0.1039	-0.5539	-0.0914	-0.1424	-0.5307	
Changes mtb proportional [%]	-0.7	-4.8	-2.9	-1.6	0.0	0.0	-1.3	-4.8	
Changes others proportional [%]	-16.8	-13.2	-14.8	-5.9	-15.0	-10.1	-7.5	-21.6	
L5PI [%]									
formal	26.75	26.76	20.32	14.63	39.73	74.12	10.91	16.10	
informal mtb	26.75	26.76	20.32	13.37	39.73	74.12	10.09	15.58	
informal others	26.50	26.76	20.30	14.61	38.73	74.12	10.80	14.59	
Changes mtb proportional	0.00	0.00	0.00	-1.26	0.00	0.00	-0.82	-0.52	
Changes others proportional	-0.25	0.00	-0.02	-0.02	-1.00	0.00	-0.11	-1.51	

5 Discussion

5.1 Informal trails in Zuerich's forests

5.1.1 Contribution of the present study

The presence of informal trails in natural areas is a common phenomenon worldwide (Wimpey & Marion, 2011a). In many cases, land and forest managers are aware of this situation, but do not have access to data concerning the spatial distribution, length and characteristics of informal trails. Spatial data on informal trails within forested areas can help managers to identify the extent and condition of existing impacts and to focus on locations potentially threatened.

Therefore, this study is aimed primarily at assessing the spatial distribution of informal trails, examining their characteristics and related impacts. To my knowledge no published research in Switzerland has examined these conditions to date. This work presents an overview of the current informal trail situation in the Zuerich area by assessing the conditions within three study areas. Further, it is aimed at investigating fragmentation effects of informal trail segments. Mapping and assessing the informal trail network in these three peri-urban forested areas result in quantitative and qualitative information about informal trail segments.

5.1.2 Impacted area and spatial extent

Prior research has focussed on spatial informal trail impacts (Leung et al., 2011; Walden-Schreiner & Leung, 2013; Wimpey & Marion, 2011a) or has analysed the impacts on vegetation, soil, forest loss or tree structure caused by informal trail networks (Ballantyne & Pickering, 2015; Barros et al., 2013). Similar to the afore-mentioned researchers, this study assessed informal trail length, disturbed area and informal trail density.

Results showed, that the total study area was affected by 19.7km of informal trail segments. Within the three study areas, total length of informal trails varied, ranging from 2.58km at the Adlisberg to 8.92km in the Sihlwald. This variation in the length of the informal trail segments is due to the large variation in size of the study areas. When impacts are normalized to account for size differences between the three study areas, the Zuerichberg was most affected by informal trailing with regard to informal trail length, total disturbed area and informal trail density. This might be due to the location of the Zuerichberg, which is enclosed by three densely populated areas. Additionally, it is easily accessible from the city centre of Zuerich. The higher occurrence of informal trails located at the boundaries of the study area, might be explained by the adjacent residential areas. Further, forest's edges, especially close to urban settlements, might be more predestined for informal trail development. The higher the density of trails (formal and informal) at forest's edges, the greater the variety of choices for recreationists within shorter time periods. Having a greater variety to choose from, visitors are more likely to use informal trails without knowledge about the impacts they cause. It is likely that visitor numbers and density per time period, time availability and appropriateness of the formal trail network are factors affecting the probability of informal trail creation at the forest's edges.

Numerically the greatest length of informal trails and the biggest area disturbed by informal trail segments were found in the Sihlwald. This is it not surprising considering the large size of this study area. However, the very low amount of informal trail segments in the centre of the Sihlwald study area, which is part of the Wildnispark Sihlwald Langenberg is interesting. Informal trail segments of the Sihlwald study area are either located at the border of the natural forest or are situated outside of the natural forest in the area of the Gattikerweier and the Morschwand region (Figure 8.8). As mentioned in 3.1, informal trail segments were not mapped within the core zone of the natural forest due to the park's policies. Even though, the amount of informal trail segments within the remaining natural forest is very low. This finding could be interpreted as a result of the forest management in the natural forest Sihlwald. As mentioned in 3.1, a wide network of user specific trails exists, giving recreationists the opportunity to exert their activities on designated trails. Trails are designed and divided into multiple-use trails and single-track trails. It seems like this network of formal trails satisfies recreationists' demands within this setting sufficiently, giving them enough room to engage in any recreational activity. The low amount of informal trails within this area can support the assumptions of Walden-Schreiner & Leung (2013) that recreationists tend to use formal trails if given a choice. However, another factor contributing to the low amount of informal trails, could be the presence of forest rangers. Rangers within this area are on duty regularly educating and informing recreationists about the rules and goals of the natural forest. It would be another question to answer, whether recreationists stay on formal trails because they are satisfied by the offer of the formal trail network presented or whether they feel obligated to stay on formal trails, knowing the consequences and impacts they cause.

In comparison to other studies focussing on informal trailing, informal trail densities in the three study areas within the present research are much lower. For example, the most dense informal trail network in this study is present at the Zuerichberg with 18.55m/ha, which is much lower than the informal trail density of 319m/ha on a meadow in the Yosemite National Park (Leung et al., 2011) and of 209m/ha in the Boston Harbor Island National Recreation Area (Manning et al., 2005). Also in comparison to a study conducted in an urban forest in Finland, where informal trail densities ranged from 100 to 200m/ha (Sievänen, 1989), the informal trail densities in this study are comparably low. In a study conducted by Ballantyne &

Pickering (2015), informal trail networks in 17 forest remnants had a trail density of 38.76m/ha (formal trail density 16.84m/ha). The low density of informal trail networks in this study in comparison to similar studies might be due to the high density of the formal trail networks within the study areas. Even though the formal trail network was not described in most studies mentioned above, maps of the study areas depict a lower formal trail network within these study areas. An additional factor in comparison to informal trailing in meadow areas can be that forested areas tend to be more confined to the creation of informal trails. Forested areas are more limited in sight, which can make it less appealing for visitors to walk off-trail. If attractive viewpoints exist, they are less visible than in open areas, such as meadows and grasslands.

5.1.3 Informal trail characteristics

Former research on informal trails characterized them by their spatial extent and distribution, as well as by trail condition classes (Leung et al., 2011; Walden-Schreiner & Leung, 2013; Wimpey & Marion, 2011a). Indicators included the total informal trail length, total informal trail extent and the informal trail density within an area. Further, Wimpey & Marion (2011a) assessed informal trail characteristics such as average width, grade, slope alignment and slope ratio. The informal trail assessment used in this study did not include trail condition classes and neither the measurement of slope alignment and slope ratio. It characterizes informal trail segments with additional attributes. Thus, a comparison with other studies is difficult and not applicable for some informal trail attributes.

Informal trail segments in this study had an average weighted width of 0.9m. Within the three study areas the average weighted width varied between 0.8 and 1.0m. These results indicate that informal trails tend to be quite narrow. Even though formal trails were not measured within this study, observations suggest that informal trails tend to be narrower than their formal counterparts. Informal trails in a study conducted by Wimpey & Marion (2011a) had a similar mean value of 0.86m. This would reinforce the results of Wimpey & Marion (2011a), finding that informal trails are significantly narrower than formal trails within their study. To validate and significantly prove this statement, formal trails would need to be measured and compared to the informal trails measured within the study area. Reasons for the smaller width could be that informal trails are not designed or maintained professionally, therefore limiting the traffic within a forest to a narrow tread by vegetation or other obstacles such as trees. Another reason could be that informal trails have a more limited use than formal trails. Heavily used trails tend to be significantly greater in width than trails used by lower traffic (Cole, 1983). Furthermore, in contrast to some formal trails, informal trails are not designed, constructed and managed to provide access for various vehicles, such as forest machinery.

Even though informal trails had an average weighted width of 0.9m, 9.4% of informal trail segments had an average width equal to or larger than 2.0m. This width might be explained by the presence of tire marks stemming from forest machinery on 8.7% of all informal trail segments. Another explanation can be the avoidance of inappropriate informal trail tread conditions (e.g. muddy conditions). Thus, trail widening is likely.

Due to non-existing trail design and lack of maintenance, informal trails have the potential to cause a greater impact than their formal counterparts (Wimpey & Marion, 2011a). As the findings of this study have shown, informal trails are generally located on steep slopes (13.3% ± 7.8%). Trail design and construction guides generally recommend not exceeding the average trail grade of 10% (IMBA, 2004; IMBA, 2007). Short sections may exceed a trail grade of 10%, as long as the average trail grade is kept lower than 10% (IMBA, 2004). Keeping this threshold is one of the key elements to design a sustainable trail. Unfortunately, since informal trails are generally constructed in absence of professional design, researchers recommend keeping the average trail grade even lower than values for formal trails, suggesting an average trail grade of 6% (Wimpey & Marion, 2011a). Regardless, the mean average slope of informal trail segments within this study exceeds both values, in total and for each of the three study areas. This makes these trails explicitly vulnerable to degradation. Trail grade significantly influences trail erosion, with steeper grades contributing to higher erosion. Steeper slopes increase the velocity of down flowing water, contributing to an increase in soil erosion down slope (Farrell & Marion, 2001).

Fall-line alignment of informal trail segments was not specifically investigated within this study. Field observations and the resultant topographical maps (Figure 8.2 to Figure 8.4). show that many informal trail segments are fall-line aligned. Fall-line aligned trails, however, have significantly higher soil loss than contour-aligned trails (Olive & Marion, 2009). Reason for this is, that water takes the path of least resistance and will flow down the fall-line instead of traversing it. Contour-aligned trails are paths contouring across a hill. They are generally characterized by gentle slopes, grade reversals and usually their treads tilt towards the downhill edge (IMBA, 2004).

Further, the attributes of steep slope and fall-line alignment and the absence of professional trail design are likely to favour trail widening, soil erosion and muddiness. This can lead to recreationists avoiding informal trail segments where these conditions are present, thus enhancing the proliferation of informal trails due to bypassing degraded trail sections and creating new informal trails. The proliferation of informal trails is especially common in high-frequented areas (Wimpey & Marion, 2011b).

Root exposure was visible on 81.6% of the informal trail segments within the study area. Exposed roots can lead to root damage and impact the health of trees (Marion & Leung, 2001). The high amount of root exposure could be linked to the fact that most informal trail segments were located on steep slopes, favouring soil erosion and soil loss, therefore exposing roots. Exposed roots cannot only decrease the aesthetic value of an area (Marion & Leung, 2001), but can also contribute to further degradation of the environment. Recreationists might experience exposed roots on informal trail segments as obstacles. Therefore, they are presented with the choice to either endure the enhanced difficulty of travel, to turn back or to find an alternative way by leaving the informal trail, starting the creation of a new informal trail. However, 81.6% of root exposure on informal trail segments seems quite high. This could be due to the applied assessment method. Root exposure was measured by indicating whether it was present or absent on informal trail segments. This method has been applied by previous researchers (Cole, 1983; Marion & Leung, 1999), but might not be precise for census-based approaches with sectional evaluation. Even though the percentage of root exposure was calculated considering the different lengths and widths of the informal trail segments (Formula 3), it still does not consider the number of root exposures on the segments. Therefore, two segments of the same length, one with a higher number and one with a lower number of root exposures are rated evenly. A more precise method would be necessary to draw more definite conclusions. Measurements such as exposed roots (in number) per kilometre could be an alternative.

Within the total study area, most informal trail segments were used by hikers (76.9%) and mountain bikers (71.2%). To date, there is no evidence that mountain biking causes a higher impact on the environment than hiking (Chiu & Kriwoken, 2003; Pickering et al., 2010a; Thurston & Reader, 2001; Wilson & Seney, 1994). However, mountain biking can cause more environmental damage by riding in inappropriate conditions (e.g. wet conditions, steep slopes) (Chiu & Kriwoken, 2003). In contrast to hiking and mountain biking, horse riding has an even greater impact on erosion (Wilson & Seney, 1994). In the present study, horse riders used 4.1% of informal trail segments within the total study area.

Many informal trails owe their beginning to recreationists. Nevertheless, informal trails currently used by humans could have been former wildlife tracks, which were subsequently used by recreationists. The formation of an individual informal trail can underlie various motives (Wimpey & Marion, 2011a). The existence of a single informal trail frequented by human traffic might encourage further recreationists to establish additional trails. Research into the causes of informal trail creation and recreationists' motivations, can be of service in supporting management decisions and thus limiting informal trail proliferation.

5.1.4 Landscape fragmentation

5.1.4.1 Informal trail-based fragmentation

Within the last decades, fragmentation effects by road networks have raised environmental concerns worldwide (Forman, 1995). Linear elements, such as roads, are dissecting landscapes by splitting up habitats or areas into smaller and smaller patches. Large mammals are often not able to sustain viable populations in small habitats. This leads to habitat and species loss and to the isolation of populations in fragmented areas. However, most research has focussed on the ecological effects of road networks on regional and landscape scale (Forman & Alexander, 1998; Mader, 1984). In some cases, linear constructions, such as trails are small elements dissecting the landscape on a local scale. The fragmentation effects of informal trails created and used by recreationists have only been discussed recently (Leung & Pickering, 2012b; Wimpey & Marion, 2011a). However, fragmentation due to informal trails is a process encountered in a number of regions around the globe (Wimpey & Marion, 2011a). Informal trails can contribute to landscape fragmentation by internally fragmenting landscape patches and decreasing their size. Furthermore, their impact can be higher than the fragmentation effects caused by formal trails, due to their tendency to fragment at a higher degree and their tendency to proliferate (Davies & Newsome, 2009; Pickering et al., 2010b).

Results of this study show that informal trails form a trail network within the forested areas affecting (0.02%) of the forest. When limiting the impacts to a linear disturbance corridor, the total area affected by informal trailing seems to be quite low. Despite the linear disturbance corridor, trails can lead to impacts not limited to linear pathways. Findings of this study show that informal trails can degrade peri-urban forest areas internally, even though the directly affected area is relatively small. The study area with a size of 23.84km^2 is already fragmented by formal trail networks into 724 isolated patches. With the contribution of informal trail networks the patch number increases to 870 patches, increasing fragmentation by 20.2%. Natural areas close to urban settlements provide critical refuges for wildlife, giving them habitat islands within agricultural areas, motorways and other urban structures. In an already fragmented area surrounded by urban development an increase in patch number by 20.2% is comparably high, considering the limited options wildlife is given to retreat.

In comparison to other studies focussing on trail-based fragmentation, the three study areas close to Zuerich are already highly fragmented by the formal trail network. For example, within the Yosemite National Park assessed meadows had an average *L5PI* of 81.7%, stating that 81.7% of the meadows are comprised by the five largest patches within the area (Leung et al., 2011). Thus, large habitat refuges are dissected. In forest remnants in the Tall

Open Blackbutt Forest in Queensland in Australia, the *L5PI* varied between 49.09% and 99.85% (Ballantyne et al., 2014b).

In the present study the average *L5PI* ranged from 10.91% at the Adlisberg to 20.32% in the Sihlwald, if only the formal trail network is taken into account. The percentage of the area comprised by the five largest patches is relatively low in comparison to the *L5PI* in the studies mentioned above. However, the difference in *L5PI* is not surprising considering that the other studies were conducted in high conservation ecosystems.

A comparative study in Australia assessed the fragmentation effects of formal and informal mountain bike trails in forest remnants in the Tall Open Blackbutt Forest. The *WMPI* decreased by 50% due to the informal trails. The *L5PI* decreased by 16.1%.

The findings of the present study had a decrease of *WMPI* ranging from 10% at the Adlisberg to 27% at the Zuerichberg, due to informal trailing. The *L5PI*, however, only decreased by 0.02% to 2.22%. The fragmentation effects due to informal trails in the present study are comparably lower. Considering the effects of fragmentation to wildlife, a decrease in the *WMPI* up to 27% might be substantial.

The fragmentation by informal trails affects the number of patches, m_{eff}, *MPS* and *WMPI* but does not seem to affect the *L5PI* substantially. As mentioned above formal trails already fragment the areas to a high degree, resulting in a relatively low amount of area comprised by the five largest patches. The low change in *L5PI* comparing the values for formal and informal trails could be explained by the relatively low amount of area comprised by the largest five patches. It seems like, the lower the *L5PI* for the formal trail network, the lower the probability that an informal trail contributes to a reduction of the area comprised by the five largest patches. Vice versa: The bigger the size of the five largest patches, the higher the probability of a single informal trail dissecting one of them. But no matter where an informal trail is located, it influences the *WMPI*, *MPS*, m_{eff} and the *Npatches*. The fragmentation indices *WMPI* and L5PI, however, show different aspects of fragmentation (Leung et al. 2011). Previous research has demonstrated that fragmentation metrics show different sensitivities based on the type of fragmentation (Jaeger, 2000; Jaeger et al., 2008). Thus, it is hardly surprising that the degree of fragmentation differs according to the used fragmentation indices even within one study area.

In the present study, the five fragmentation indices *L5PI,* number of patches, *MPS, WMPI* and m_{eff}, were applied. Results indicate that the Zuerichberg is most affected by fragmentation due to informal trails within the total study area. An increase of 36.6% in the number of patches and a reduction of 27.3% in the *WMPI* highlight how informal trails can fragment peri-urban forest areas internally. The decrease in *WMPI* can be explained by the high increase in the number of patches (60).

Regarding the number of patches, *MPS* and *WMPI* the lowest informal trail based fragmentation is visible at the Adlisberg. The lower increase in the number of patches is responsible for the smaller decrease in *MPS* and *WMPI* in comparison to the Zuerichberg study area.

When comparing the fragmentation indices for the three study areas, forest areas are fragmented by informal trails unproportionally. However, the difference in the values of the fragmentation indices among the three study areas might be explained by the proximity to urban settlements, transportation infrastructures and easier accessibility. The Zuerichberg is likely to receive and attract more visitors than the other two study areas, because of the proximity to highly populated urban settlements. However, further research with a higher number of forest areas across an urbanisation gradient is needed to assess this assumption and to justify it with statistical results. Visitor access and access points might contribute further to trail-based fragmentation. The more access points exist, the higher the trail densities within an area (Priskin, 2003). Furthermore, it would be interesting to assess the number of access points within the area and correlate it with the number of informal trails within an area.

Non-motorized roads have less disturbing effects on natural populations and ecosystems (Forman & Alexander, 1998). However, results of the present study show that informal trail networks can create distinctive spatial patterns and decrease the number of intact habitat patches (*WMPS*) substantially, thus altering the spatial patterns and ecosystem processes within an area.

Informal trail based fragmentation is definitely of higher concern in high conservation ecosystems. But it has also to be considered in peri-urban forest areas with lower conservation status. Results of the present study highlight, that informal trail networks can cause additional internal fragmentation in forests close to urban settlements. Habitat patches get fragmented into smaller and smaller pieces, each exposed to greater edge effects. This can lead to various ecological effects (Forman, 1995). Therefore, informal trail networks reduce the capacity of these forests to persist as functional ecosystems. This is particularly problematic, when these forested areas act as habitat refuges, enclosed by dense populated settlements.

The presence of informal trails can also present barriers for wildlife. While such effects are likely to be less in comparison to motorized traffic roads and other transportation infrastructures, informal trails can still pose a threat to species sensitive to disturbances. Thus informal trails might reduce the ecological integrity.

Within the present study, informal trails do not seem to isolate areas from the surrounding habitat due to their narrow width and non-motorized conditions. Even though, impacts on wildlife cannot be excluded. Small species (e.g. beetles) or species with low dispersal rates or species sensible to disturbances are likely to be more affected.

5.1.4.2 Fragmentation of roe deer habitat

Recreational activities in forested areas can affect wildlife negatively by entering their natural habitat and disturbing their peace. Hiking, mountain-biking, horse-riding, nature-watching and other recreational activities are known to be directly and indirectly responsible for the disturbance of wildlife. Direct impacts of wildlife to human-disturbances include modifications in behavioural patterns and avoidance of several areas. Behavioural changes of wildlife can include “flight” responses, increased alertness, spatial and temporal displacement, food conditioning and habituation to people (George & Crooks, 2006; Marzano & Dandy, 2012). Human disturbance can affect fitness and energetic balances of animals, as well as foraging and mating behaviour (Knight & Cole, 1991; Marzano & Dandy, 2012; Taylor & Knight 2003). Indirect impacts include habitat changes due to soil erosion and compaction, introduction of invasive species, weeds, pathogens and pests, decreased biodiversity, habitat fragmentation and canopy loss (Marzano & Dandy, 2012).

Generally, recreational activities off-trail lead to a higher disturbance and stronger responses of wildlife, including higher flushing probability (Miller et al., 2001; Taylor & Knight, 2003). Hikers induce a more intense response of wildlife than motorized vehicles, whereas the quiet and fast mode of travel of mountain bikers is less predictable for wildlife (Taylor & Knight, 2003). Other studies revealed a higher response of wildlife to hikers in comparison to mountain bikers (Papouchis et al., 2001). Some species respond to recreational use of trails by shifting their occurrences along trails from day to night (George & Crooks, 2012).

The findings of this study show that informal trails affect wildlife habitat by dissecting home ranges of roe deer into smaller areas. Due to the different spatial patterns of informal trails, home ranges of roe deer are affected differently. Depending on the locations of the informal trail within wildlife habitat, impacts might be severe, e.g. by dissecting the largest undisturbed habitat patch within the home range area of the species or even by leading through the core area. The core area is located within the home range of the species. It can be defined as the area receiving concentrated use and occupied by a 50% probability by an individual (Laver & Kelly, 2008; Samuel et al., 1985). Within the home range, species use the space disproportionately (Samuel et al., 1985). Disturbances by recreational activities can cause behaviour, activity and heart rate changes in roe deer. Roe deer react with short intense responses to optical disturbances, with normal behaviour within a few minutes after the disturbance (Reimoser, 2012). Thus, it seems likely, that the location of informal trails as well as the frequency and intensity of their usage play a major role in the impact they cause on wildlife. Formal trails already affect the distribution and abundance of species. Species sensitive to human disturbance may occur in reduced abundance and in further distance from the trail (Miller et al., 2001). If the disturbance by humans is predictable, wildlife might even habituate (Taylor & Knight, 2003). However, in cases of informal trails, their usage can often be unpredictable. Findings from the present study show that informal trails on average were quite narrow, mostly suitable for one-person traffic. One-person trails may be more likely to be used by recreationists seeking peace and quiet. Without making noise and therefore warning wildlife, human presence on these informal trails might be less predictable, thus, causing a greater impact. Furthermore, some informal trails were leading through thicket. By activity on these trails, wildlife might be caught off-guard in very close distances to the trail. Keeping this in mind, recreational activity on informal trails might cause higher disturbances to wildlife in comparison to human activity on formal trails (Taylor & Knight, 2003).

How severe the impacts of informal trails on wildlife are, has still to be investigated. It is likely, that the severity of impacts will depend on the location and spatial distribution of informal trails, as well as on trail width and frequency of usage. As results by researchers focussing on formal trails have shown, there is little difference in the response of wildlife to hiking and mountain biking. Similarities between flight and alert distance, as well as the distance to move between hiking and mountain biking were identified (Taylor & Knight, 2003). Wildlife tends to react most to the upright position, with hikers triggering more intense reactions of wildlife than motorized vehicles, whereas the quiet and fast mode of travel of mountain bikers tends to be less predictable for wildlife (Taylor & Knight, 2003).

The research group “Wildlife Management” of Graf from the ZHAW in Wädenswil, is already examining the space-time behaviour of ungulates and humans within the same area in the Sihlwald (ZHAW, 2015). Further research should investigate if behavioural patterns of roe deer distinctly change, due to informal trails. Are the informal trails used frequently enough to change behavioural patterns over time? Does each usage of an informal trail cause flushing and intense reactions in roe deer?

5.2 Informal mountain bike trail segments

5.2.1 Contribution of the present study

To my knowledge, this is the first study analysing how informal mountain bike trail segments differ from informal trail segments used by other user groups within the same area. Prior research has focussed on the comparison between formal and informal mountain bike trails and their effects on degradation and fragmentation (Ballantyne et al., 2014a) and on measuring the extent of informal mountain bike trails and trail technical features (Davies & Newsome, 2009).

5.2.2 Impacted area and spatial extent

Results from the present study reveal that more than one fifth (22.1%) of the total area disturbed by informal trail segments, is caused by off-trail mountain biking. Informal mountain bike trail segments account for 4 109m of the total study area, with the Zuerichberg contributing to the highest proportion of informal mountain bike trail segment and the highest informal mountain bike trail density. Informal trail segments used by mountain bikers exclusively (22.1%) were comparably less than informal trail segments used by other user groups (79.9%). Within the three study areas, mountain bikers used a total of 71.2% of the informal trail segments. This is a large share, considering the impacts off-trail mountain biking might cause.

5.2.2.1 Sihlwald

Informal trail segments used exclusively by mountain bikers were not identified in the natural forest Sihlwald. Generally, it seems like the forest management applied effective measures to limit the construction of informal trails as mentioned in 5.1. As I experienced myself, forest rangers provide maps to visitors and explain to them the situation and management goals of the natural forest. This and the provision of user-specific trails seem to be reasons for the absence of informal mountain bike segments within this part of the study area. However, outside of the natural forest, informal trail segments used exclusively by mountain bikers are situated in the S/SW at the border between canton Zuerich and canton Zug, just on the boundary to the natural forest Sihlwald. Reasons for the location of these informal trails could be, that they are easily accessible. Furthermore, by being located on the border, it might be unsure in which area of forest management responsibility they fall. The incorporation of TTFs (n=8) on these informal trail segments might be a sign that users are looking for more technically challenging terrain. Specific mountain bike trails in the natural forest Sihlwald do not incorporate TTFs. Even though user frequencies have not been assessed within the framework of this study, observations suggest that the informal trail incorporating eight TTFs is used frequently.

5.2.2.2 Adlisberg

Since 2013 a formally established mountain bike trail, incorporating TTFs, with a length of 2.4km exists at the Adlisberg. The former informal mountain bike trail is still visible incorporating six TTFs (Figure 8.6). Most measures to prevent usage (10.3%) of informal trails within the study areas were found at the Adlisberg. It seems like these measures were based on the management decision to close the informal mountain bike trail. Further research on user frequencies on the informal mountain bike trail and the new formally established one could provide feedback about the effectiveness of management measures.

5.2.2.3 Zuerichberg

Informal trails used by mountain bikers at the Zuerichberg are mostly located in close proximity to urban settlements. Off-trail mountain biking used 70.3% of informal trail segments. Even though it was not analysed in this study, observations reveal that mountain bikers also used steep formal hiking trails in the NE of the study area. By incorporating these formal trails, mountain bikers are able to connect informal trail segments with the formal trail system, extending the length of the ride. Thus, they enhance the degradation of formal trails.

5.2.3 Trail technical features

Study findings reveal that unique off-trail impacts caused by mountain biking are the construction of unauthorized trail technical features in all study areas and mountain bike skid marks. Each study area had a least one informal trail, consisting of segments with trail technical features. Other researchers analysed TTFs on all trails within their study area (Kollar, 2011; Pickering et al., 2010b). However, in comparison to their studies, TTFs within the present study area were identified within a larger study area and their number was comparably low (29). Due to the original focus of this thesis I expected to find a higher number of TTFs on informal trail segments in the study area.

The size of structures with an average length of 1.78m, 1.09m average width and 0.38m average height was smaller than in the formerly mentioned studies. The average dimensions of trail technical features were 2.7m in length, 2.2m in width and 0.56m in height (Pickering et al., 2010b). In contrast, TTFs assessed by Kollar (2011) had a mean length of 10.3m, 2.0m maximum height and 1.6m maximum width at the montane site and a mean length of 6.0m, 9.1m in maximum height and 1.7m in maximum width at the coastal plain site.

Construction material in the present study was mostly from natural sources, including local vegetation and soils. Only in two cases external material was brought to the site. In comparison to Pickering et al. (2010b), no wood harvest and nearly no import of foreign material was connected with the construction of TTFs.

The relatively low number of TTFs might demonstrate the effective management in the present forest study areas. One of those measures might be the provision of alternative options for challenging trails. Within the Sihlwald study area mountain bike specific trails exist. At the Adlisberg a formal mountain bike trail incorporating trail technical features was established in 2013. Furthermore, at the Zuerichberg a pump track for technical experienced riders was established (Figure 8.7). A pump track is a looping trail system with berms and rollers. Its goal is to gain and maintain speed through pumping motions by the rider's upper and lower body, without pedalling.

The low number of TTFs could also be an effect of sharing limited space between users, exercising different recreational activities. If unauthorized trail technical features are built and located at places visited by other user groups, they might get reported to foresters or land managers or even get destroyed.

It has to be kept in mind that TTFs are an addition to the impact caused by the informal trail segments within the study areas. Unauthorized trail technical features still add 8.6% to the total disturbed area caused by off-trail mountain biking.

5.2.4 Comparison of characteristics among informal segments used exclusively by mountain bikers and informal segments used by other user groups

Results from the present study showed that informal segments used exclusively by mountain bikers were significantly steeper, had a significantly higher side-effect of trail width and had significantly higher values for the maximum trail incision in relation to other informal trail segments. Due to these attributes, it seems like informal mountain bike segments are more problematic and can be associated with more erosion related impacts in comparison to other informal trail segments. Further, impacts increase under wet conditions (Chiu & Kriwoken, 2003).

Poor contour alignment often induces soil loss (Wimpey & Marion, 2010). Additionally, steeper slopes induce a higher amount of soil loss in comparison to shallower trail slopes (Farrell & Marion, 2001). Former research results show that steeper slopes significantly lead to increased incision (Goeft & Alder, 2001; White et al., 2006; Wilson & Seney, 1994). Increased incision leads to channelled water runoff, exacerbating the degradation of the trail tread. By skidding or bad breaking habits, mountain bikers initiate soil loss by loosening substrate and thus contribute to soil degradation by creating ruts and central grooves on trails (Chiu & Kriwoken, 2003). Frequent use of informal trail segments by mountain biking can exacerbate soil-related impacts caused by informal trails.

However, the significant difference in slope between informal mountain bike segments and informal trail segments used by other users is not surprising, since mountain bikers tend to prefer trails with steeper slopes (Goeft & Alder, 2001).

The difference in width was only significant at the Zuerichberg. Informal segments used exclusively by mountain bikers tended to be narrower than informal trails used by other user groups. By having a smaller width they should affect less area than other informal trail segments. In comparison to other studies, informal mountain bike segments in the present study were comparably narrower in width (mean and sd). Informal mountain bike segments in a study conducted by Ballantyne et al. (2014a) had an average mean width of 2.9m ± 1.8m.

5.2.5 Fragmentation by informal trail segments used exclusively by mountain bikers

Informal trail segments used exclusively by mountain bikers were lower in number (n=31) in comparison to informal trail segments used by other user groups (n=159). The higher increase in *Npatches* and the higher decrease in *MPS* and *WMPI* due to the fragmentation by informal trail segments used by other user groups can be explained by the higher amount of these segments within the study area. However, regarding the m_{eff} and *L5PI* it is apparent that informal segments used exclusively by mountain bikers at the Adlisberg, fragment the area to a higher degree. The *L5PI* decreases higher for informal segments used exclusively by mountain bikers due to one segment dissecting one of the five largest habitat patches (Figure 4.7), resulting in a decrease of the area occupied by the five largest patches. In comparison to the *MPS* and the *Npatches*, the m_{eff} decreases at the Adlisberg higher for informal segments used exclusively by mountain bikers. This could be explained by the characteristics of the fragmentation metrics. The m_{eff} is insensitive to very small patches, whereas the *MPS* and *Npatches* are sensitive to all patches independent of their size (Jaeger, 2000). Furthermore, as mentioned in 5.1.4.1, fragmentation metrics differ in their sensitivity depending on the kind of fragmentation process (Jaeger, 2000; Jaeger et al., 2008).

As results show, informal trails used by other user groups fragment the study area to a higher degree in comparison to informal mountain bike trails. However, this is highly due to the extent and number of the informal trail segments used by others. Even though informal trails used exclusively by mountain bikers are less in number (8) than informal trails used by others (29), fragmentation due to informal mountain bike trails at the Adlisberg is greater based on the values for m_{eff} and *L5PI*. This indicates that the spatial location of the informal trails can play a major role in the degree of fragmentation they cause within an area. Thus not only the amount and linear length of informal trails contribute to the severity of fragmentation.

5.3 Management implications

5.3.1 General management implications

In order to make justifiable decisions, managers require spatial information about informal trail networks. Informal trail assessments result in data documenting the spatial distribution of informal trail location. Managers may find this information essential for setting priorities for taking action or to justify management actions. It is important to reduce the impacts caused by informal trailing not only to the linear disturbance corridor within an area but to regard the informal trails as disturbing objects within a landscape. The fragmentation indices are important and effects of informal trailing can be better explained by including them to enhance the current understanding of problems caused by informal trail networks within areas.

The severity of impacts caused by informal trails in different areas and regions is affected by several factors. It can depend on the conservation value of the site, the tolerance of the ecosystem and on soil conditions (Pickering, 2010). Furthermore, impacts of informal trails within an area can vary, due to the frequency, type and seasonality of use, as well as climatic variables (Monz et al., 2010; Pickering, 2010). The severity of impact depends mostly on the location of an informal trail and the frequency of usage (Pickering et al., 2010a; Pickering et al., 2011).

Managers of forest areas have to be aware that informal trails are formed rapidly when recreationists leave the formal trail. They need to know where their threshold of informal trail approval is. As we have seen in this study, by being able to compare informal trail segments from three areas, spatial distribution, density and length within areas vary. To determine an informal trail threshold, they need to know and consider the attributes of the informal trail segments. In preparation, managers could answer questions such as: To which extent did the offer of the formal trail network fail? How much informal trail density do we want to accept? Do informal trails lead through sensitive areas? To which extent do they fragment wildlife habitat? Do they exceed the recommendations for sustainable trails from trail building guides? Should the informal trails be closed? Or could they be tolerated to this extent? Does the benefit of informal trail usage outweigh the consequences and impacts (e.g. informal trail leading to places for outdoor kindergardens)?

From a managerial perspective, as results of the present study have shown, it is important to consider the impacts caused by informal trails, due to their effects of linear disturbance and the effects they cause across the landscape. Managers have to consider which informal trails should be closed to reduce the fragmentation of sensitive habitats and large undissected patches. As mentioned in 5.1, informal trail impacts need to be limited, especially in sensitive areas. Educational means are especially important to inform visitors where sensitive habitats for wildlife and plants are situated. I suggest, that signs should indicate not to leave the formal trails to emphasize the importance of these sensitive habitats.

The construction of a formal trail network satisfying the whole range of recreationists within a natural area, while minimizing environmental impacts is challenging for managers (Davies & Newsome, 2009). Informal trail proliferation impedes mastering the balancing act between trail sustainability and recreationists' demands. Replication of informal trail assessment would provide information about changes in their location and trail condition over time. Analysis from continuous monitoring could identify trends and evaluate the effectiveness of implemented management actions.

5.3.2 Management options

There are several options open to managers to deal with existing informal trails. Managers are presented with choices to minimize or avoid impacts including the closure of the informal trails, educating recreationists, converting and relocating informal trails and creating formal trails as alternatives. Another option is to leave the informal trail as it is. However, this is likely to result in the proliferation of informal trails and does not prevent further environmental damage. An attitude of disinterest towards informal trail creation from management's side might be interpreted as the allowance to create further informal trails.

To counteract informal trail constructions, it might be of advantage to combine one or more of the following management options: Closure of informal trails, providing education to recreationists, converting informal trails into formal ones and enhancement of formal trail maintenance or construction of additional formal trails to satisfy recreationists' needs.

Closure of informal trails

If informal trail segments are rated inappropriate from management side, they should be immediately closed and recovery actions should be initiated where needed. Especially, informal trails leading through sensitive and fragile areas should be avoided, as well as those with steep slopes. One possibility to close an informal trail originating from a formal one is to place obstacles, such as logs or rocks, at its entry and exit points. By skilfully placing obstacles at the junction between formal and informal trail segments, recreational traffic will be concentrated to the formal tread surface. Additionally, sight in direction of the informal trail might be prevented. Recreationists will either realise that the informal trail should not be entered or at best not even recognise it. By combining signs and obstacles, recreationists could be informed about the reasons for trail closure. Signs next to or on the surface of the obstacle could be used to educate visitors, such as: “Help us preserve wildlife habitat and natural resources on this informally developed trail. Please keep off! Thank you!”.

To ensure the closure of an informal trail it is important to know the intention behind its construction. If it was created to access a specific point of interest, managers should consider making this location accessible by providing an appealing formal alternative.

The Grün Stadt Zürich (GSZ) used this option recently. In June 2013, the GSZ opened a new formal mountain bike trail at the Adlisberg to construct an alternative to the established informal one. The new trail was built by engaging a local mountain bike association (ZüriTrails). The former informal trail was leading through sensitive wildlife areas. Especially in the lowest section, informal trail construction proliferated more and more. With the provision of the new formal trail, the management hopes to prevent the usage of the informal one. Furthermore, with the creation of the formal alternative, management unbundles trail segments used by bikers and hikers, to minimize social conflicts among user groups (Stadt Zürich, 2015).

Education

Providing education to recreationists should discourage informal trail proliferation. It is essential to make recreationists aware of the impacts they cause by leaving the formal trail network. I believe that in many cases visitors do not know that they impact the environment by engaging in off-trail activities. Therefore, education can be supported by putting up information panels at the main entrance and exit points of a recreational area. Further, it is essential to improve formal trail markings. In some cases it is difficult to distinguish a formal trail from an informal one. By providing adequate trail markings, this problem can be resolved and recreationists will be aware whether they are utilizing a formal trail or not. These examples could be part of an educational strategy, which should reduce the probability of creating new informal trails and re-opening closed ones.

Converting informal trails into formal ones and incorporating them into the formal trail network

Under some circumstances, informal trail segments may be rated appropriate. In these cases managers could consider to formalize these trails. Informal trail segments should be evaluated based on trail slope, trail alignment and trail location. Avoiding steep downhill sections by relocating inappropriate sections reduces environmental impacts. Steep sections should be relocated to trail slopes under 10%. For short sections, steeper slopes could be tolerated as long as the overall trail slope does not exceed the 10% guideline (IMBA, 2004). Informal trails with fall-line alignments should rather be closed instead of being converted into a formal alternative. Fall-line aligned trails tend to already be degraded to a higher extent than contour aligned trails. Normally, trying to relocate and redesign them in a sustainable way is expensive. Depending on the location and condition of the trail, the hardening of the informal trail surface to prevent the development of muddy conditions and to limit soil erosion should be considered. Soil erosion on trail steeper than 11% is significantly higher on trails with little or no gravel cover (Olive & Marion, 2009). However, it must be kept in mind, that trail hardening is costly and can result in further environmental damage (Ballantyne & Pickering, 2015).

Enhancement of formal trail maintenance or construction of additional formal trails to satisfy visitor's needs

Informal trails might be created to avoid unfavourable conditions on formal trails, such as muddiness or root exposure. In these cases, managers have the option to enhance the design of the formal trail network and increase the maintenance effort of the latter. By providing a well-maintained trails, visitors might be less likely to leave them due to unappealing trail conditions.

5.3.3 Mountain bike specific management implications

The sustainability of mountain biking especially in areas close to urban settlement is only ensured on formally established trails. These trails should be designed and build according to the recommendations for sustainable trail building to minimize environmental impact and designed to satisfy rider preferences (IMBA, 2004; IMBA, 2007).

As we have seen, informal mountain bike trail segments are located on steeper slopes, have higher incision and have higher side-effects of trail width than other informal trail segments. Therefore, management attention should focus firstly on informal mountain bike trail segments, due to their potential for higher degradation. Managers are presented with the same choices as mentioned in 5.3.2.

Special attention should be put on the education of mountain bikers. Closing informal trails used by mountain bikers without any explanation could lead to incomprehension and might trigger aggression towards the management. It is important to make riders aware of the reasons why specific measures have been taken. If informal mountain bike trails are used frequently, management should consider whether it could be possible and appropriate to redesign it to a formal mountain bike trail, concentrating mountain bike riders on a well-designed and sustainable trail. Redesigning, trail planning and building should be done in cooperation with riders. A sustainable trail design includes the appropriate design of curves to minimize the potential of erosion through skidding. A diversified well-managed formal alternative could minimize the creation of mountain bike specific informal trails and unauthorized construction of trail technical features. However, it is important that the formal alternative is managed in such a way that broken features are replaced and deteriorated trail conditions are restored quickly. Collaboration between managers and mountain bikers is important to minimize conflicts and to ensure effective maintenance. By giving mountain bikers the opportunity to integrate their preferences and knowledge into the trail building process and leaving them the option to incorporate and modify the trail with various trail technical features after consultation with management, it is likely that informal mountain bike trails will disappear.

TTF construction especially close to large urban areas can cause major mountain bike specific impacts to the environment (Davies & Newsome, 2009; Kollar, 2011; Pickering et al., 2010b). Even though the number and size of TTFs within the present study is comparably low, managers should still monitor the construction of unauthorized trail technical features on informal trails. Poorly designed TTFs can be accompanied with a higher risk for riders and pose a threat to recreationists' safety. Furthermore, if located in sensitive areas not designed for biking, TTFs represent an additive impact on the environment by contributing to area loss and by concentrating technically skilled riders to informal trails.

From this observation and the locations of the informal trail segments used by mountain bikers within this study area it seems like there is a need to respond to the unspoken demands of bikers using this area. 70.3% of informal trails at the Zuerichberg are used by mountain bikers. This could indicate that there is a need for more challenging features. It seems like the establishment of the pump track at the Zuerichberg, was an attempt to satisfy this demand. However, this measure might not have been sufficient or even might have been counterproductive. Until now riders ideally entered and exited the pump track using formal multiple-use trails. However, by riding the pump track the riders might even get more motivated to continue riding on technically challenging terrain, preferably on formal trails. For me it seems like the formal trails adjacent to the pump track do not provide such a challenge. Without the provision of technically challenging formal trails exiting the area, riders might intentionally create informal trails to satisfy their longing for technical challenge. Furthermore, bikers might ride faster on multi-use trails exiting the pump track, looking for further challenges.

This example can show that management measures for a specific user group should be considered in a larger context to be effective.

5.4 Limitations

5.4.1 General limitations

This study sought to collect spatial data on informal trails in three peri-urban study areas. Informal trail assessment can provide detailed data about trail characteristics and geographically referenced data. However, this study only examined the status of informal trails at the time of the assessment, giving a current snapshot of the situation. Informal trails can proliferate and change their locations over time (Walden-Schreiner & Leung, 2013). This limits the validation of the data over time and repetition of informal trail assessment would be needed at a later stage.

In addition, the user type of the informal trail segments was only assessed by walking the informal trail segments once, recording visible traces. Depending on the weather and soil conditions, traces were more visible. Thus, it cannot be ruled out that more user types than those recorded, make use of the informal trails. For a precise analysis of informal trail users, user types have to be assessed frequently. Further, this study did not provide data about the frequency of use and the age of the informal trails, which could influence the impact they cause. To include the frequency of use could be important for management decisions. It could be of help to consider which appropriate informal trails might be worth converting into formal trails, due to high visitor traffic.

Another constraint is that informal trails were recorded in segments. This assessment resulted in averaged data representative for the entire segment, which leads to some inaccuracies. More accurate measurement methods are point-sampling methods, which require more time for the selected study area, but provide more accurate and precise information. The applied method of assessing the sight in various directions from the trail did not seem appropriate for long segments. Therefore, the data was not included in the result chapter. By averaging the sight distance for long segments, the measure does not seem accurate. Different approaches or a sampling method assessing the sight from the trail at frequent intervals seems more applicable. With this information, the potential for wildlife to take cover can be estimated. It must be stated that this information is just a current snapshot of the vegetation cover present at the time of the assessment.

This assessment recorded informal trail segments starting or ending at formal trails. Informal trail segments crossing other recorded informal trail segments were included in the assessment. However, the assessment is not exhaustive. The possibility of missing informal trail segments cannot be excluded. Even though most informal trails are used and created by recreationists, some, however, might be created by wildlife (Leung et al., 2011). These formed trails appear similar to informal trails, drawing visitor's attention towards them. With the usage of low traffic, they quickly form into apparent informal trails, contributing to informal trail proliferation. If human traces were visible, the former wildlife trail was recorded and mapped as an informal trail.

The GPS accuracy varied. Thus, inaccuracies in the exact spatial location of informal trail segments and trail technical features are present.

Furthermore, this study only assessed the impacts caused by informal trails and trail technical features. It did not take into account impacts caused by the creation of outdoor kindergardens and the creation of campfire locations. Within the present study, informal trails were often leading to destinations such as campfire places or playgrounds from outdoor kindergardens (Figure 8.9). To assess their contribution to the impacts caused by informal trails, would be of interest and might be of concern for management.

5.4.2 Mountain bike specific limitations

The impact caused by off-trail mountain biking was only assessed on the informal trail segments, which were used exclusively by mountain bikers. However, trail technical features from all informal trail segments were included. Therefore, to assess the total impact related to mountain biking on informal trails, the impacts caused by informal trail segments used exclusively by mountain bikers and the additional impacts caused by TTFs were analysed. It did not include informal trail segments shared by multiple users. However, as results have shown mountain bikers use a total of 71.2% of the informal trail segments, while only 22.7% are used exclusively by mountain bikers. This can distort the picture. Mountain biker’s contribution to the overall impact is likely to be higher than the thesis presents, but difficult to assess on multiple-used informal trail segments.

Furthermore it has to be considered that the informal trail segments used exclusively by mountain bikers were low in number, in comparison to informal segments used by other user groups. 11 informal segments used by mountain bikers exclusively were recorded in the Sihlwald, 8 at the Adlisberg and 12 at the Zuerichberg. To enhance the statistical representativeness, more informal trails used by mountain bikers exclusively in other forested study areas close to Zuerich should be included.

5.5 Outlook

This thesis built a basis for assessing informal trail networks in peri-urban forested areas around Zurich. Future informal trail assessments may use the information found in this study. Due to the knowledge of the location of informal trails in the study area, further investigation regarding the condition of informal trails could be done. For example, impacts of informal trails on soil loss and vegetation change could be examined. Further analysis of study data may identify vulnerable areas threatened by the identified informal trails in this study. This could inform managers and help them decide how to proceed with the informal trail problem. Long time monitoring could be applied to detect changes in informal trail patterns in the study areas between the years. Temporal evaluation would be especially useful in sensitive areas vulnerable to disturbances and changes.

The applied assessment approach was based on identifying informal trail segments from the formal trail network and was applicable for the size of the study area. However, the selection of measures could be adapted for different conditions (e.g. condition class rating, occurrence of muddy conditions) and management goals.

Due to the unknown level of usage and critical attributes such as steep slopes, informal trail segments may pose a greater threat to the loss of natural area than formal trails. Further research is needed to compare their impacts with impacts caused by formal trails, to quantify and evaluate the impacts more precisely, and to investigate their effects on a greater range of conditions. The results of the present study can be regarded as a data basis. Further procedure could include discussing these findings with forest management within the study areas. Based on forest development plans and management goals, the current status of informal trails should be discussed and evaluated. Furthermore, applying a point-sampling method to informal trail segments in sensitive forest areas could provide more detailed information and could identify the impacts of these segments on vegetation, soil and forest loss. Forest managers could evaluate the impacts and have to consider how to deal with the informal trails in their area. In future, repetition of informal trail assessment can provide information about an increase or decrease in informal trail proliferation and could be of help to evaluate applied management measures.

6 Conclusion

This research sought to investigate the characteristics of informal trails and assess their spatial distribution and fragmentation effects in three forested areas adjacent to urban settlements close to Zuerich. Furthermore, it was investigated how informal trail segments used explicitly by mountain bikers differ from those used by other user groups. To examine the impact caused by off-trail mountain biking, trail technical features were additionally assessed.

Results highlight how informal trails dissect forested areas close to urban settlements and result in additive disturbance area. Even though the linear disturbance might be limited, results of this study show that depending on the location and distribution of informal trails, their contribution to landscape fragmentation might be substantial. Significant differences between informal trail segments among user types occur. However, whether the differences are related to the type of use or influenced by other factors was not investigated.

Impacts caused by informal trails within these forested areas seem trivial in comparison to those caused by forest clearance, but they should not be underestimated. Although impacts of informal trails are mostly limited to a linear disturbance corridor, they increase in severity when fragmenting sensitive areas and habitats. The impacts in the investigated forested areas were discussed, but not evaluated and rated within the framework of this study. Further proceedings would include discussing the present findings with local forest managers and to implement management measures where needed.

Forest managers have to be aware that the number of informal trails can increase rapidly near urban areas. Even low levels of usage can already contribute to forest degradation and result in severe impacts to vegetation as well as soil (Ballantyne et al., 2014b; Thurston & Reader, 2001; Weaver & Dale, 1978). Through knowledge about the location and characteristics of informal trails, managers can implement measures to achieve a better balance between forest protection and satisfaction of recreationists' demands. The results of this study provide scientifically grounded data, which can serve as a foundation to help forest managers get an overview of the informal trail situation within their area, to facilitate their decision-making, and to determine appropriate measures that need to be taken. Consequently, management strategies such as informal trail closure, informal trail conversion and relocation and enhancement of formal trail maintenance could avoid or minimize the creation of additional informal trails. Furthermore, the development of a visitor educational program is advisable to ensure the effectiveness and efficiency of management measures. Public involvement and collaborative trail planning can increase the awareness of the negative impacts caused by informal trails and might minimize consequences.

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8 Appendix

Table 8.1 (I): Informal trail assessment.

Variable	Data scale	Method	Categories
Basic information			
ID line feature	nominal	ID according to study area	The first informal trail segment starts with 0X-001-00-00 Sihlwald X=1 Adlisberg X=2 Zuerichberg X=3
Date	interval	date	
Datetime	interval	datetime	
Photography number(s)	number		
GPS coordinates (starting point)	WGS84 datum	Assess with GPS device	
GPS coordinates (end point)	WGS84 datum	Assess with GPS device	
GPS accuracy	numerical	Assess with GPS device ; in [m]	
GPS device used			
Informal trail (general information)			
Type of use	nominal	Assess; Multiple selection possible	Hikers Mountain bikers Horse rider Forest use Other
Trail width average	metric	Measure using measurement tape [m]	
Side-effect of trail width+	metric	Measure side-effects of trail width separately if existing	
Average slope	metric	Assessed in ArcGIS [%]	
Total length	metric	Assessed in ArcGIS [m]	
Vegetation			
Sight trail surrounding (right)	metric	Assess in [m]	
Sight trail surrounding (left)	metric	Assess in [m]	
Sight trail within trail direction	metric	Assess in [m]	
Sight trail opposite of trail direction	metric	Assess in [m]	

Table 8.1 (II): Informal trail assessment.

Variable	Data scale	Method	Categories
Forest type	nominal	Assess;	Deciduous (d) Mixed (m) Coniferous (c)
Trail surface	nominal	Assess; Multiple selection possible	Forest soil Sawdust Grass Roots Stones Gravel loose Gravel solid Other
Forest edge	nominal	Assess	Present Not present
Damaged trees	nominal	Assess	Present Not present
Environmental impacts			
Root exposure	nominal	Assess	Present Not present
Presence of rubbish	nominal	Assess; Multiple selection possible	None Appliances Vehicles Electronics Glass Metal Plastics Other
Maximum trail incision	metric	Assess in [m]	
Skid marks	nominal	Assess	Present Not present
Additional area of disturbance	metric	Assess in [m]	If p.e. due to avoidance of muddy sections, a short optional path is formed
Total disturbed area		Calulated in ArcGIS. *Formula= Length of segment (Trail width + sideeffect of trail width*	

Table 8.1 (III): Informal trail assessment.

Variable	Data scale	Method	Categories
Safety factors and management issues			
Presence to prevent using this trail	nominal	Assess	Present Not present
Photography number which shows preventing usage			
Remarks			
Start of this assessment	interval		
End of this assessment	interval		

Table 8.2 (I): Trail technical feature assessment.

Variable	Data scale	Method	Categories
Basic information			
ID point feature	numerical		
Date	interval		
Datetime	interval		
Photography number(s)	numerical		
GPS coordinates	WGS84 datum	Assessed with GPS device	
GPS accuracy		Assessed with GPS device	
GPS device used			
Trail technical feature			
TTF group (technical opportunity)	nominal	Assessed	GROUND= Natural surface TRAVERSE= elevated artificial or enhanced surface AERIAL= Above surface or aerial
Type of feature (according to riding opportunity)	nominal	Assessed	Bridge Camber Ditch Drop-off Berm Jump Ladder Ladder bridge Mound Log See-saw Combination Other
TTF type (naturalness)	nominal	Assessed	NATURAL= natural obstacle p.e. log, which was at this particular site and has been incorporated into the informal trail without moving or modification ENHANCED NATURAL=natural resources, which have been replaced or recombined or even brought to the side ARTIFICIAL= built out of foreign material, engineered

Table 8.3 (II): Trail technical feature assessment.

Variable	Data scale	Method	Categories
Size of feature *Width (max)*	metric	Measured in [m]	
Width (min)	metric	Measured in [m]	
Height (max.)	metric	Measured in [m]	
Height (min.)	metric	Measured in [m]	
Length (max.)	metric	Measured in [m]	
Construction material	nominal	Assessed	Concrete
			Drums
			Local vegetation
			Metal
			Soils
			Imported timber
			Other
TTF location to trail	nominal	Assessed	On track
			Cleared vegetation
Width of trail at TTF	metric	Measured in [m]	
Sideeffect of trail (width+)	metric	Measured in [m]	
Slope (grade) of trail at TTF	metric	Measured with a distance measuring device	
Aspect	metric	Measured with a distance measuring device in [°]	
Rollable	nominal	Assessed	Yes
			No
Vegetation			
Condition understory	nominal	Assessed	Poor
			Good
			Thick vegetation
Ground cover	nominal	Assessed	Grass
		Multiple selection	Saplings
		possible	Needles
			Shrubs
			Adult trees
Canopy type	nominal	Assessed	Open= 0-25% cover
			Mixed= 26-74% cover Closed=75-100% cover

Table 8.2 (III): Trail technical feature assessment.

Variable	Data scale	Method	Categories
Environmental impacts			
Disturbed area	metric	Measured and calculated	
Trail depth (entrance)	metric	Measured in [m]	
Trail depth (exit)	metric	Measured in [m]	
Removal of native vegetation	nominal	Assessed	Present Not present
Root exposure	nominal	Assessed	Present Not present
Presence of skid marks	nominal	Assessed	Present Not present
Presence of rubbish	nominal	Assessed	None Vehicles Electronics Glass Metal Plastics Other
Safety factors and management issues			
Condition of feature	nominal	Assessed	Like new Good Poor
Safety of feature	nominal	Assessed	Low Moderate High Very high
Presence of signage	nominal	Assessed	Present Not present
Presence of filters, choke points	nominal	Assessed	Present Not present
Presence of fall zones	nominal	Assessed	Present Not present
Presence of optional lines	nominal	Assessed	Present Not present
Presence to prevent using this particular TTF	nominal	Assessed	Present Not present
Photography number preventing usage			
Remarks			
Metadata			
Start of this assessment			
End of this assessment			

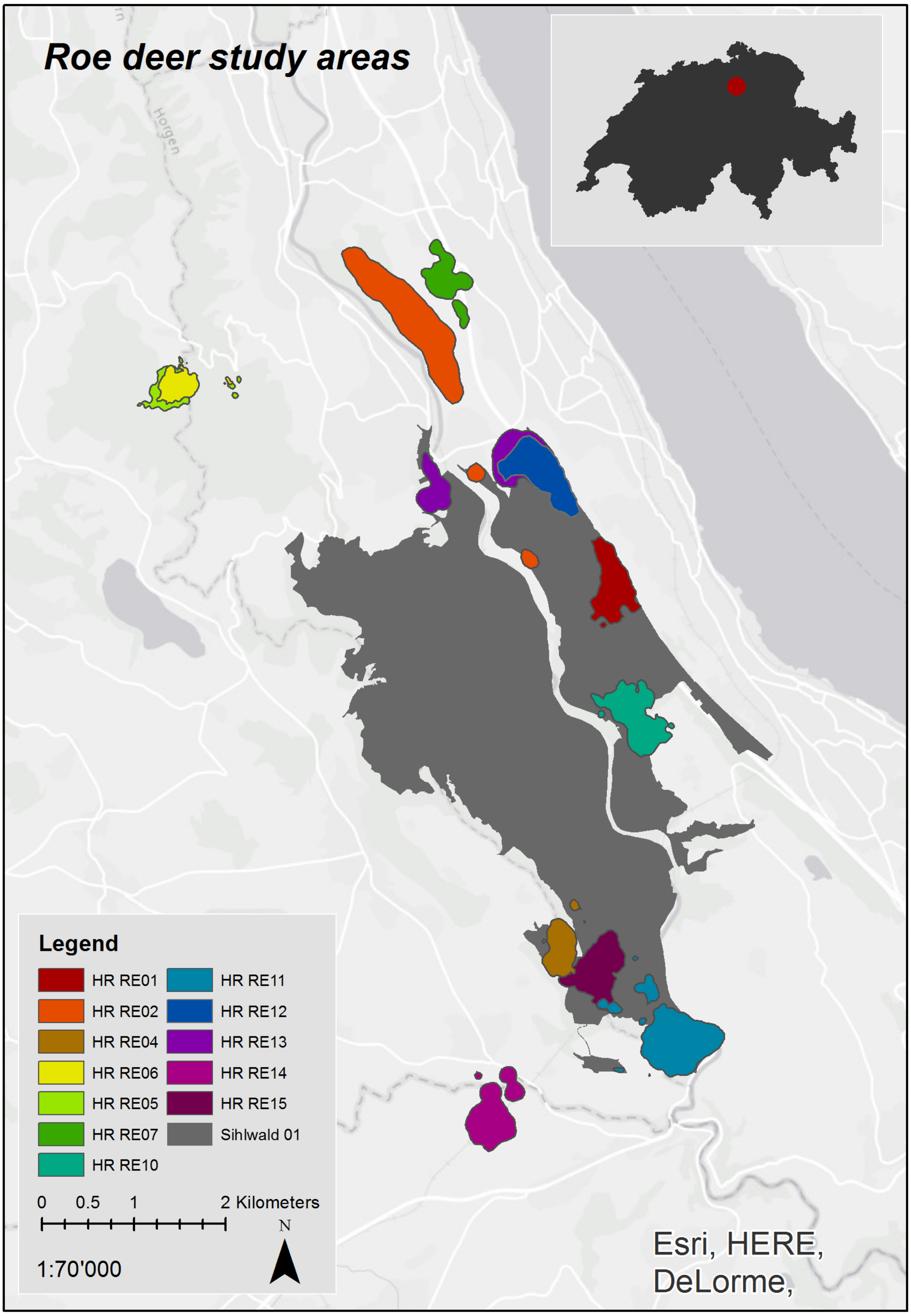

Figure 8.1: Study areas roe deer.

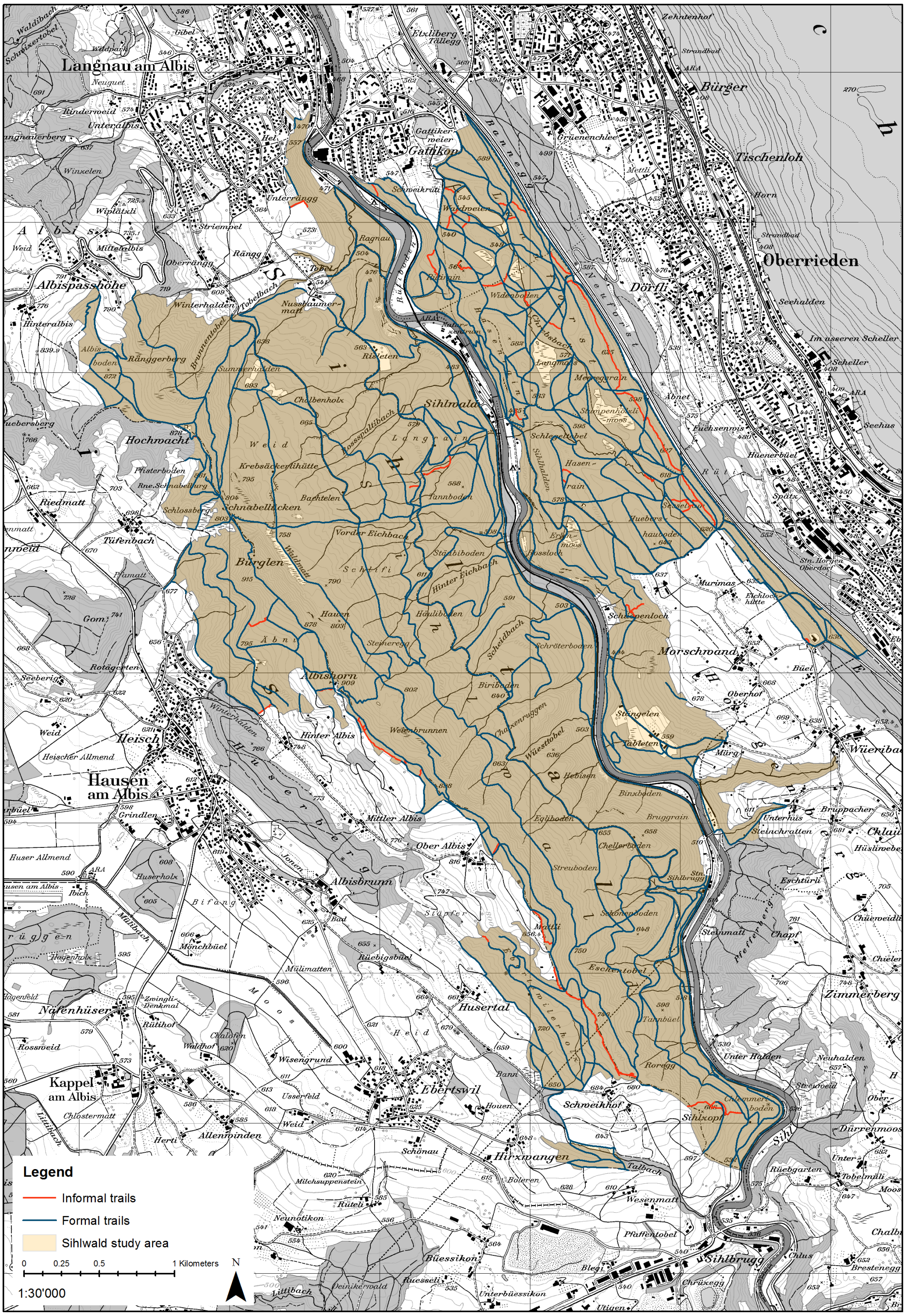

Figure 8.2: Informal trails in the Sihlwald.

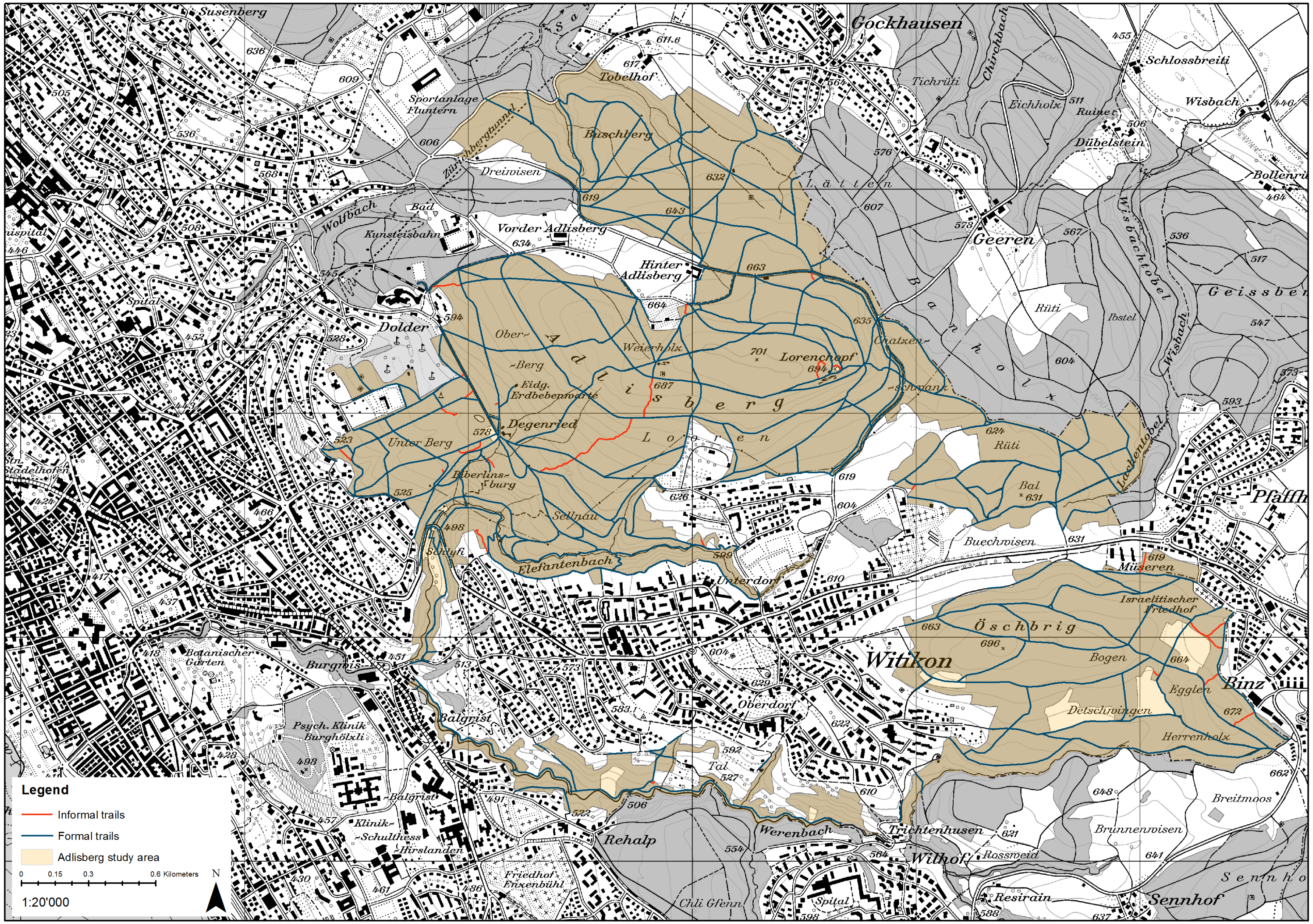

Figure 8.3: Informal trails at the Adlisberg.

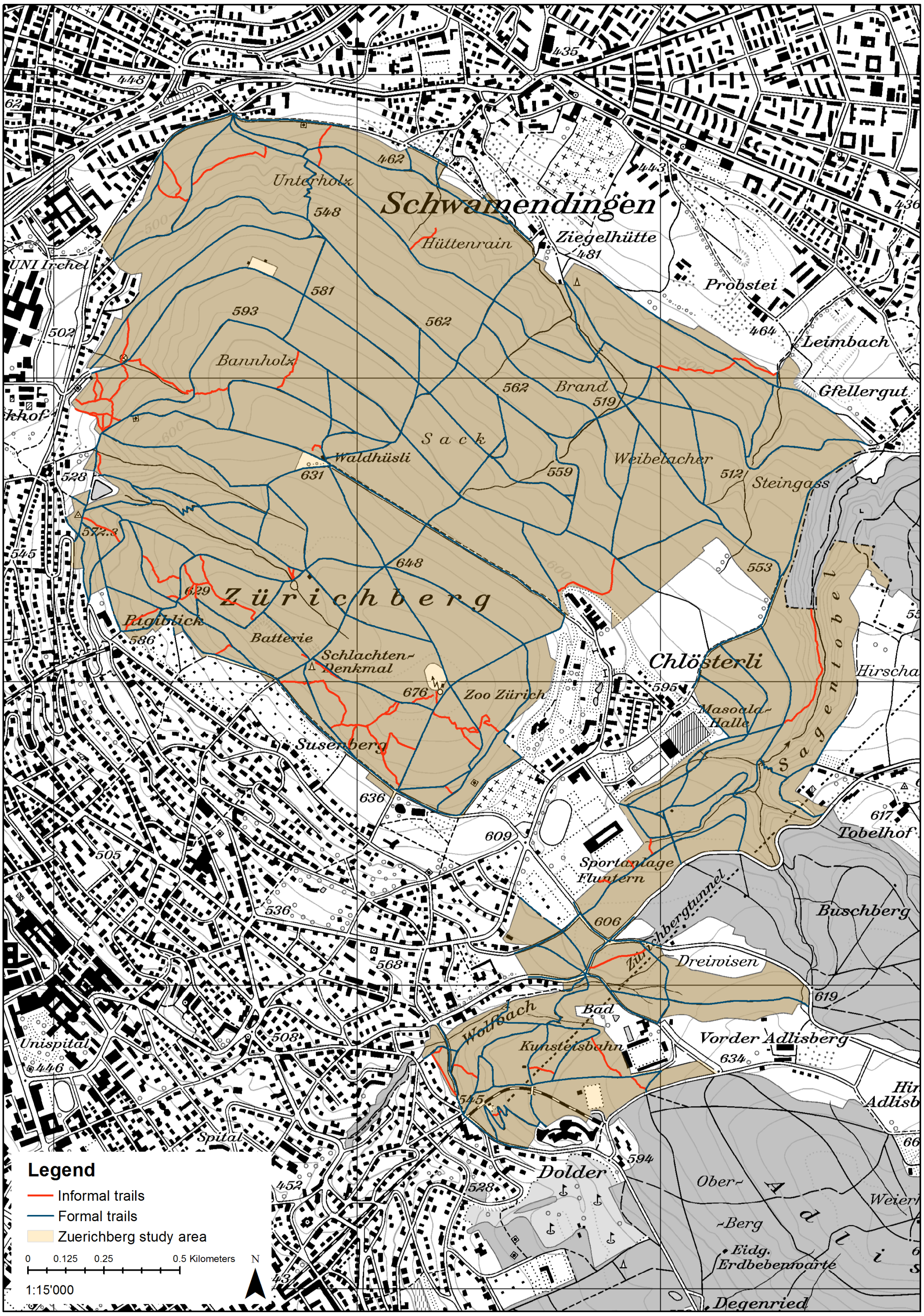

Figure 8.4: Informal trails at the Zuerichberg.

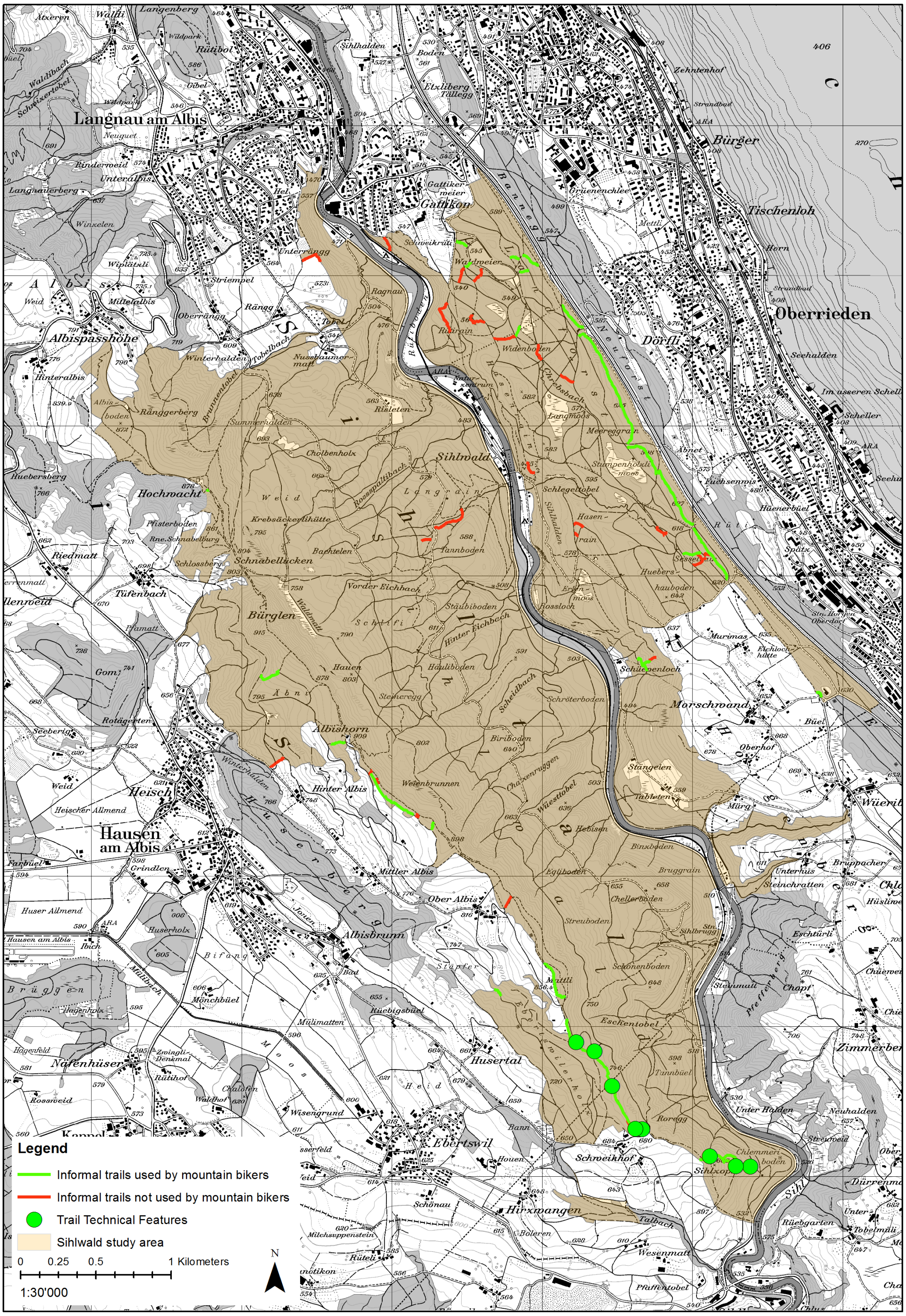

Figure 8.5: Informal trails used by mountain bikers in the Sihlwald.

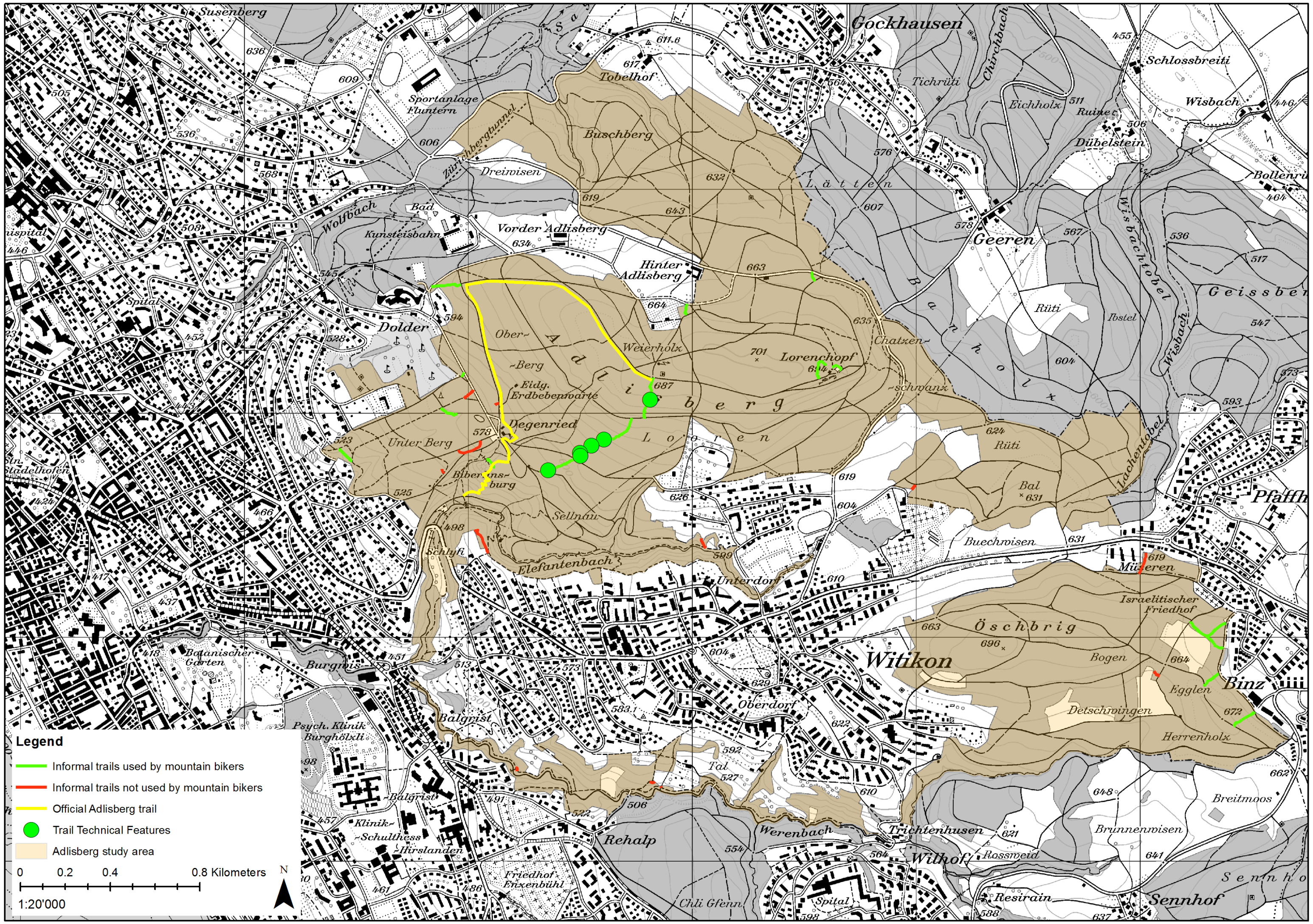

Figure 8.6: Informal trails used by mountain bikers at the Adlisberg.

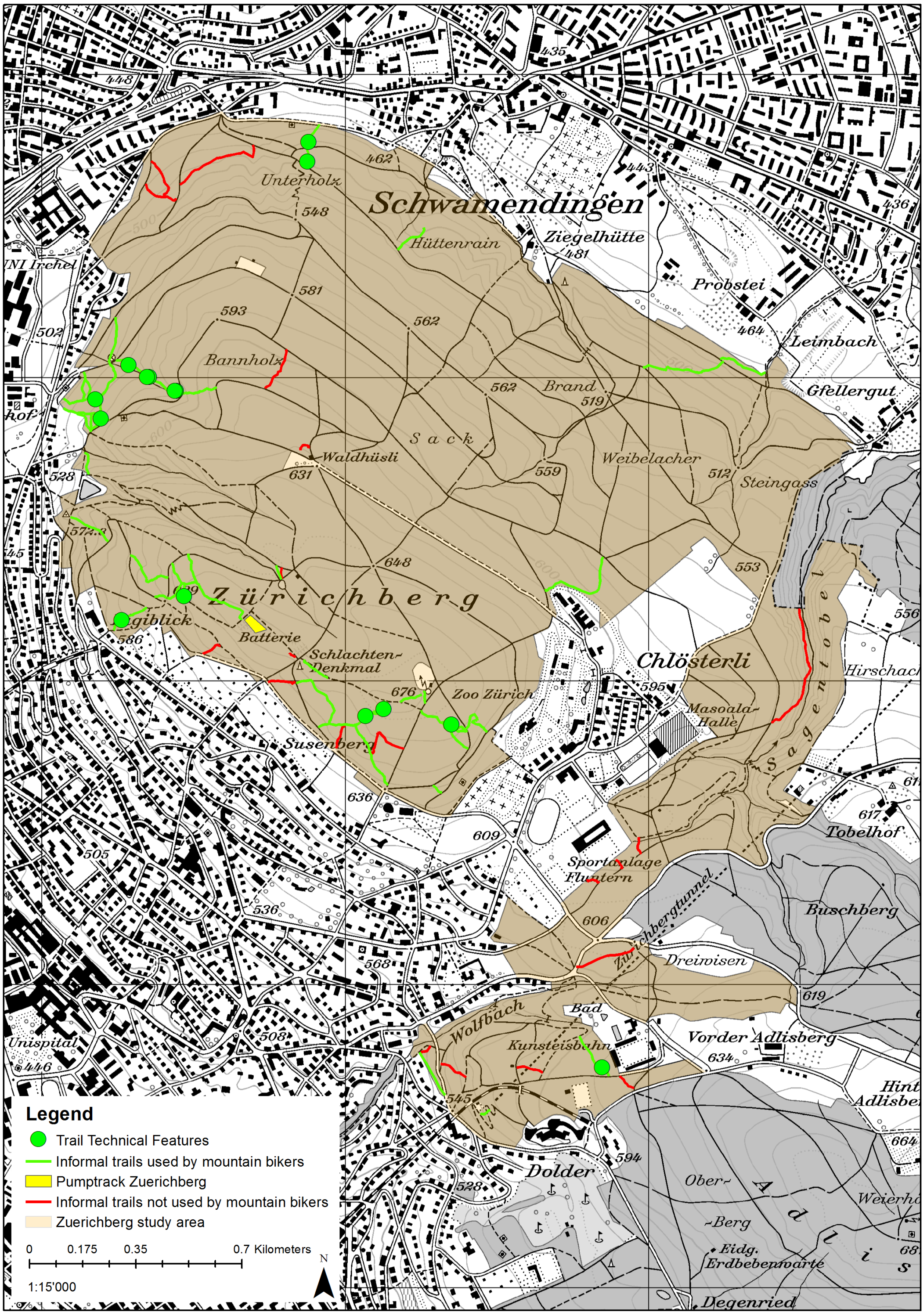

Figure 8.7: Informal trails used by mountain bikers at the Zuerichberg.

Table 8.3 (I): Results of the Trail Technical Feature assessment.

	Sihlwald	Adlisberg	Zuerichberg	Total
Number of TTFs	8	6	15	29
TTF group				
Ground	1	2	4	7
Traverse	0	0	2	2
Aerial	7	4	9	20
Type of feature				
Jump	3	4	5	12
Log	2	0	6	8
Drop-off	3	0	0	3
Berm	0	1	1	2
Bridge	0	0	1	1
Ladder bridge	0	0	1	1
Log steps	0	1	0	1
Others	0	0	1	1
TTF type (naturalness)				
Natural	6	0	0	6
Enhanced natural	1	2	13	16
Artificial	1	4	2	7
Size of feature [m]				
Width(max)	1.04 ± 0.39	1.17 ± 0.47	1.09 ± 0.43	1.09 ± 0.42
Height (max.)	0.76 ± 0.72	0.34 ± 0.11	0.26 ± 0.13	0.38 ± 0.43
Lenght (max.)	1.04 ± 0.72	2.23 ± 0.88	2.01 ± 1.67	1.78 ± 1.38
Construction material				
Local vegetation	5	5	14	24
Soils	5	5	12	22
Imported timber	0	2	0	2
Stones	1	1	2	4
Others	1	0	0	1
TTF location to trail				
On track	7	4	10	21
Cleared vegetation	1	2	5	8
Width of trail at TTF [m]	1.14 ± 0.52	1.32 ± 0.70	0.92 ± 0.55	1.07 ± 0.58
Sideeffect of trail (width +) [m]	0.18 ± 0.49	0.37 ± 0.6	0.07 ± 0.16	0.16 ± 0.39
Slope at TTF [%]	-4.4 ± 7.2	-8.7 ± 7.3	-8.2 ± 6.0	-7.2 ± 6.6
Rollable	3	3	8	14
Vegetation				
Condition understory				
Thick vegetation	3	0	6	9
Good	0	5	6	11
Poor	5	1	6	9

Table 8.3 (II): Results of the Trail Technical Feature assessment.

	Sihlwald	Adlisberg	Zuerichberg	Total
Ground cover				
Shrubs	3	1	0	4
Saplings	5	5	6	16
Grass	0	6	9	15
Needles	0	1	0	1
Canopy type				
open	0	0	5	5
mixed	3	6	7	16
closed	5	0	3	8
Environmental impacts				
Area of bare soil				
Total	23.9	24.7	25	73.6
Area without understory				
Total	0	14.7	4.2	14.9
Trail incision (entrance)	0.04 ± 0.06	0.00 ± 0.01	0.02 ± 0.03	0.02 ± 0.04
Max.	0.15	0.02	0.08	
Trail incision (exit)	0.02 ± 0.03	0.04 ± 0.05	0.01 ± 0.03	0.02 ± 0.03
Max.	0.08	0.12	0.09	
Removal of native vegetation	1	1	4	6
Root exposure	4	5	2	11
Presence of rubbish	0	0	0	0
Disturbed area single TTF [m2]	1.2 ± 1.0	2.8 ± 1.8	2.1 ± 1.7	2 ± 1.6
Total disturbed area TTF [m2]	26.4 ± 44	8.7 ± 5.8	7.7 ± 13.9	13.1 ± 25.6
Safety factors and management issues				
Condition of feature				
Like new	0	0	3	3
Good	5	3	8	16
Poor	3	3	4	10
Safety of feature				
Low	1	3	0	4
Moderate	4	1	7	12
Good	0	2	0	2
High	3	0	0	11
Presence of signage	0	0	0	0
Presence of filters, choke points	0	0	0	0
Presence of fall zones	0	0	1	1
Presence of optional lines	6	4	6	16
Presence to prevent using this particular TTF	1	0	1	2

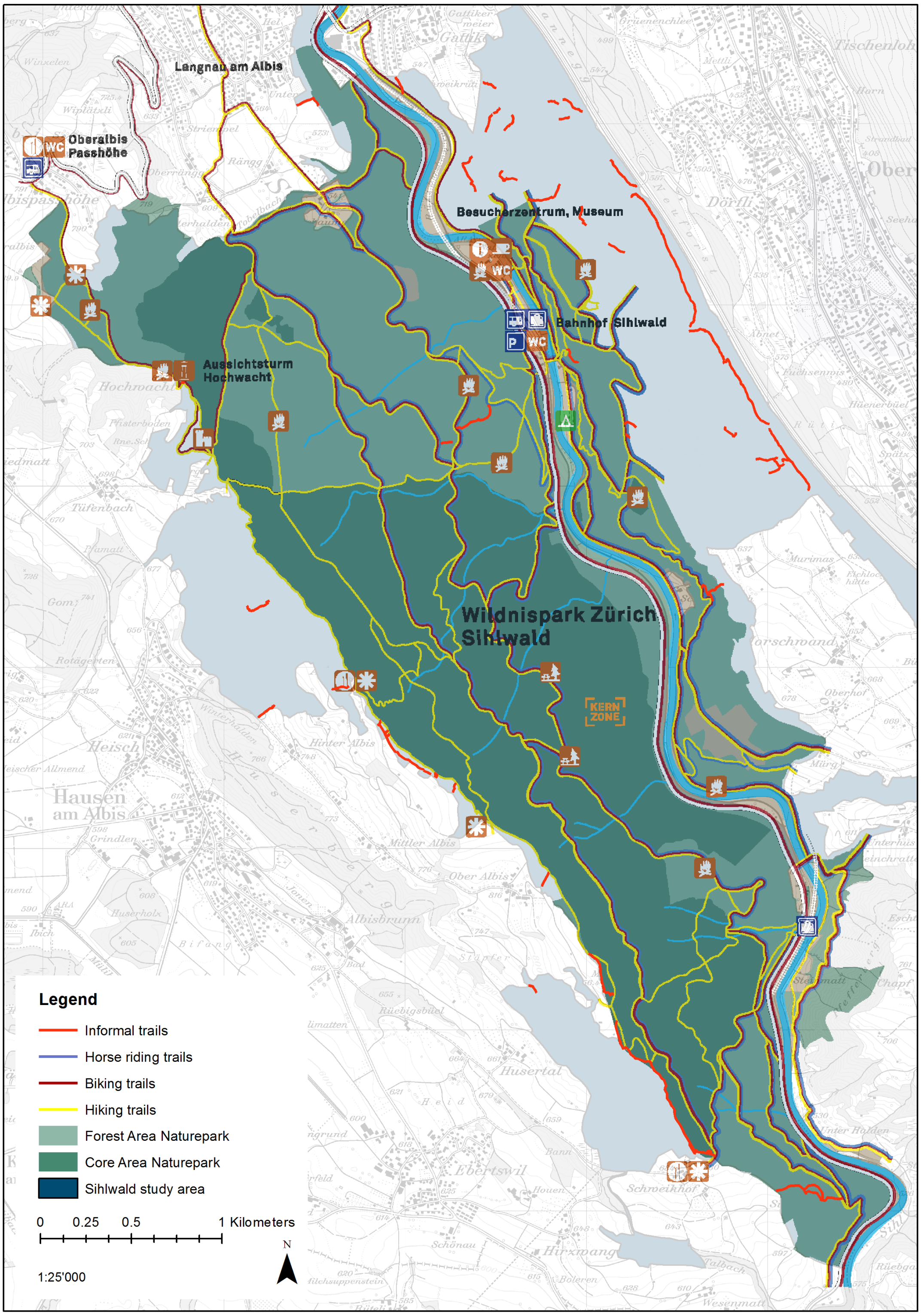

Figure 8.8: Informal trails within the natural forest Sihlwald.

Figure 8.9: Other constructions within the study area.

9 Glossary

Term	Abbreviation	Description/Definition
Area of influence		The area, wherein wildlife (e.g. birds, deer) may be disturbed in their behavioral patterns and may be displaced from their usual habitat due to recreational activities. In the area of influence animals might react by fleeing from the disturbance by leaving their prime habitat and moving to a secondary habitat.
Berm		A steeply banked insloped turn with a concave tread surface. (Kollar, 2001; IMBA, 2015).
Core area	CA	It can be defined as the area within the home range of an animal receiving concentrated use, and occupied by a 50% probability by an individual.
Disturbed area		The area affected directly by informal trails and/or TTFs. The disturbed area does not include the area of disturbance in a broader sense, which includes the *area of influence.*
Drop-off		Obstacle and TTF, with a perpendicular, vertical drop from one trail tread to the following trail tread. The rider drops from one level to a lower level (PAMBA, 2004; SportsDefinition, 2011)
Effective mesh size	m_{eff}	This landscape fragmentation metric expresses the probability of two randomly chosen points within an area to be found in the same unfragmented region.
Environmental System Research Institute	ESRI	ESRI is a software development company of GIS mapping software(ESRI, 2015). Products can be summarized with the name ArcGIS and include ArcView, ArcEditor, ArcInfo (ArcMap and ArcCatalog), as well as ArcReader and ArcGISExplorer.
Formal trail		Trail, which is designed, constructed and maintained to provide access to formerly inaccessible areas and to concentrate visitor traffic to designated tread surfaces (Marion & Leung, 2011; Wimpey & Marion, 2011b; Wimpey, 2009). In this thesis: Trail, which is designated in the topographic map 1:25 000 of the Swiss confederation.
Home range	HR	The area occupied by an individual with a 95% probability during a specific period.
Informal trail		Trail, which is distinguishable and consists of continuous visitor created trail segments.

		Other terms are social or unofficial trail. It is neither designed nor included in the formally managed trail system (Leung, 2002). In this thesis: User-created unmanaged trails, with the starting point located on a formal or other informal trail and the endpoint located either on a formal or informal trail or leading to a specific point of interest. It is neither designated in the formal trail system of the topographic map 1:25 000 of the Swiss confederation, nor planned or approved by land managers.
Largest 5 Patches Index	*L5PI*	This landscape fragmentation metric is expressed as the sum of the area of the largest five patches divided by the total landscape area, multiplied by a hundred.
Mean Patch Size	*MPS*	The mean patch size of (isolated) patches within an area.
Off-trail mountain biking		In this thesis the term solely refers to mountain biking off formal trails/roads, using informal trails. It does not include riding off-trail (formal and informal) over free and “untouched” terrain.
Pumptrack		A looping trail system with berms and rollers, where the goal is to gain and maintain speed through pumping motions by the rider’s upper and lower body, without pedalling.
Shapefile		This vector data storage format is used in GIS for storing the location, shape and attributes of geographic features (ESRI, 2015).
Side-effect (of trail width)		It includes the effects of trail widening, such as trampling of vegetation or removal of organic litter due to trail traffic and is additionally measured to the average trail width.
Trail Technical Feature	TTF	Trail technical features are obstacles, which are constructed on or besides trails to enhance the technical challenge for riders.
Weighted Mean Patch Index	*WMPI*	This landscape fragmentation metric is a modification of the *MPS.*

Glossary references

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Declaration

I, Miriam Herten, herewith declare that I have written this paper on my own and that I have not used any other sources and materials than those indicated. I properly cited the materials I have relied upon. I have not submitted this document as a master thesis elsewhere.

Freiburg, 9th of October , 2015

Miriam Herten