How Fractal Complexity Distorts Distance and Elevation Gain in Trail and Mountain Running: The Case for Course Measurement Standardisation

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Abstract

Research Question:

Trail and mountain running (TMR) is a rapidly growing and increasingly professionalized sport. However, the absence of a common standard for measuring race courses creates inconsistencies in distance and elevation gain metrics. This study investigates how fractal complexity affects these measurements at varying GPS resolutions and emphasizes the need for standardized course measurement protocols in TMR.

Research Methods:

GPX files from 34 UTMB World Series race courses, including final events in Chamonix, were analysed. Horizontal distance, elevation gain, km-effort, and fractal complexity were computed at varying GPS spatial resolutions (0.2–100 m). Elevation data were refined using a 20-cm Digital Elevation Model (DEM) to minimize errors. Courses were systematically resampled and compared to assess the effects of spatial resolution on race measurements and classifications.

Results and Findings:

The findings reveal that a decrease a in the spatial resolution of GPS measurements leads to significant reductions in measured horizontal and vertical distances, with discrepancies of up to 10%. These inconsistencies affect race course classifications, athlete benchmarking, and performance comparisons across different events.

Implications:

This study highlights the importance of standardising GPS spatial resolution to improve the accuracy and consistency of trail and mountain running race measurements. Adopting a 1-metre resolution would enhance the reliability of distance, elevation gain, and km-effort calculations, ensuring fairer race classifications and comparability across events. The proposed methodology can also benefit other sports and disciplines that rely on precise course measurements, such as cycling, hiking, and skiing, by reducing discrepancies caused by varying measurement protocols.

1. Introduction

The rising popularity of Trail and Mountain Running (TMR), along with other running disciplines in natural terrain—such as sky, fell, ultra, or cross-country running—has inspired thousands to connect with natural environments, fostering efforts to further develop and organise the sport.

TMR courses, often set in diverse and rugged topographies, vary widely in distance, cumulative elevation gain, technical difficulty, and complexity. This variability introduces a unique challenge: the irregular and self-similar (fractal) structure of mountain geography impacts the accuracy of distance measurements, both horizontally and vertically (Skinner, 2020).

The fractal nature of geographic features is well-documented in scientific literature (Mandelbrot 1998, Lam & Quattrochi 1992). A renowned study by Mandelbrot (1967) demonstrated how attempts to measure the coastline of Great Britain yielded varying distances depending on the spatial resolution of the measurement. This concept applies to TMR courses, where intricate and repeating patterns in the terrain make distance and elevation measurements highly sensitive to the spatial resolution of course data, typically obtained from global positioning system (GPS) devices (Li, 2014) or Geographical Information Systems (GIS). Even minor changes in resolution can result in substantial differences in reported distances and elevation gains, as reported by Skinner (2020), where the total distance of the Appalachian Trail decreases as the spatial resolution increases.

Two consecutive points on a TMR course, recorded with a spatial resolution of 10 metres, imply that the athlete's trajectory between them is a straight line. However, the irregularity of natural terrain often makes this assumption inaccurate. If the segment were measured at a finer, human-scale resolution (e.g., 1 metre), the recorded distance would increase, capturing the fractal complexity of the terrain.

In road running, established standards for measuring distance and altitude ensure consistency and comparability across events (World Athletics & AIMS, 2023; Corbitt et al., 1964). Tools like the Jones Counter, which measures distances by rolling a standardized wheel along the course, account for both horizontal and vertical displacement, providing accurate three-dimensional measurements for official races. While these mature and widely adopted methods ensure precision in road running, they cannot be used effectively in natural environments with irregular and uneven terrain.

In contrast, GPS devices commonly used in TMR, calculate distance based on a two-dimensional model, treating the vertical components of rugged terrain as a separate measure, referred to as elevation gain. This distinction can lead to discrepancies between official distances recorded for road races and those measured by commercially available GPS devices, particularly on hilly courses.

Research indicates that GPS devices tend to overestimate road distances by 0.04% to 0.28% (Vallan & Realpe, 2022). While this level of accuracy aligns with the minimum uncertainty requirements set by World Athletics, GPS is recommended only for validation purposes in road race measurements rather than as a primary tool (World Athletics & AIMS, 2023). In natural terrain, the importance of GPS resolution becomes more pronounced for accurately measuring distances (Li, 2014) and elevation gain (Campbell et al., 2019). Campbell et al. (2022) observe that high-frequency GPS points may introduce noise, while low-frequency points fail to capture terrain-travel rate relationships. Rampinini et al. (2015) further highlight the impact of sampling frequency on GPS accuracy, noting that only devices with a 10 Hz frequency provide sufficient precision for quantifying distances in team sports, particularly as accuracy diminishes with increased speed. Similarly, Gløersen et al. (2018) demonstrate that speed influences positional deviations in ski data, with higher sampling frequencies improving accuracy.

To enhance data quality and accuracy, some studies have implemented latitude-longitude corrections to improve distance estimation in pedestrian locomotion (Campbell et al., 2022). Others have explored the use of Digital Elevation Models (DEM) for obtaining and imputing elevation data (de Smet et al, 2018; Sánchez & Villena, 2020; Sánchez et al., 2024). However, in TMR there is currently no consensus on best practices for measuring either distance or elevation gain.

Derived from Naismith's Rule (Scarf, 2007), the kilometre-effort formula—widely adopted by the International Trail Running Association (ITRA)—adds 1 kilometre of effort (km-effort) for every 100 metres of elevation gain to approximate the physical demands of a course. Using this metric, ITRA classifies races into standardised categories, such as S for Short (45–74 km-effort), M for Medium (75–114 km-effort), L for Long (115–154 km-effort), XL for Extra Long (155–209 km-effort), and XXL for Ultra Long (210 km-effort or more). To refine these estimations, more advanced hiking formulas have been proposed, incorporating factors like elevation loss, a nonlinear relationship between slope and speed, or the impact of altitude on route difficulty (Prisner & Sui, 2023; Kay, 2012; Emig & Peltonen, 2020; de Smet et al., 2018). Nevertheless, these methods rely heavily on the consistent and accurate measurement of both distance and elevation gain.

This paper addresses a critical gap in the literature regarding the standardization of spatial resolution for TMR course measurement. The absence of consistent standards complicates event comparison and course classification, limiting the sport's formal development. A standardized framework would enable fair comparisons and provide sports scientists with reliable tools to study athletes in real-world environments, enhancing our understanding of athlete's performance.

Given this context, the aim of this paper is to assess how spatial resolution influences the measurement and classification of trail and mountain running courses, with a focus on its implications for distance, elevation gain, and race categorisation.

The specific objectives are:

1. To characterise the current variation in spatial resolution, distance, and elevation gain across UTMB World Circuit, one of the major global TMR event series.
2. To examine how race distances, elevation gains, and kilometre-effort values change across a wide range of spatial resolutions, comparing these to values derived using a human-scale 1-metre spatial resolution standard.
3. To assess the impact of adopting a 1-metre spatial resolution standard on race classification systems, particularly concerning ITRA's race categories.

2. Methods

2.1. Assessing variation in spatial resolution across the UTMB circuit

The dataset consists of GPX files published online by races within the Ultra-Trail du Mont-Blanc (UTMB) World circuit (UTMB, 2024), which is the most established trail and mountain running series worldwide. For each race event, the longest available distance was selected, resulting in a total of 34 GPX files from different UTMB circuit races available as of November 2024. All distances from the final event, which start and/or finish in Chamonix, France (TDS, CCC, UTMB, OCC, MCC) were also included.

For each GPX file, the distance between two consecutive points was calculated using the cosine-haversine formula (Robusto, 1957), which provides the horizontal distance without accounting for vertical displacement. For simplicity, we will refer to horizontal displacement as distance. Vertical displacement between consecutive points was calculated separately, which can result in elevation gain or elevation loss.

For the entire course, total distance, cumulative elevation gain, and cumulative elevation loss were computed. The spatial resolution of each course was defined as the average horizontal distance between consecutive points. The kilometre-effort of the course was calculated using the cumulative elevation gain and total distance, based on Naismith's formula (Scarf, 2007).

The percentage of measurements with no horizontal displacement between consecutive points was determined (% of idle time) as a measure of data quality. Additionally, elevation gain and loss during idle time were analysed, revealing instances of spurious elevation gain attributed to measurement errors and sensor recalibration.

The fractal complexity of each course was calculated using the periodogram estimator (Chan, 1995), offering a measure of the course's geometric complexity.

Finally, a descriptive statistical analysis was conducted, reporting global means, standard deviations, quartiles, and median values for all described variables.

2.2. Comparing kilometre-effort, distance and elevation gain across spatial resolutions

To compare courses at different spatial resolutions, we first resampled all GPX files to the highest resolution of 0.2 metres using linear interpolation. This method was chosen to avoid potential bias introduced by model-based interpolation techniques. Once all courses were resampled to a 0.2-meter resolution, they were systematically down sampled to resolutions ranging from 0.2 to 100 metres, resulting in 500 versions of each course across the resolution spectrum.

To minimize inconsistencies in elevation data, elevation values for each course at each resolution were derived from a Digital Elevation Model (DEM), following the methodology outlined in previous studies (Sanchez & Villena, 2020, Menaspà et al., 2014). The DEM used in this study was sourced from the Shuttle Radar Topography Mission (SRTM) (NASA, 2013), which is globally available and offered at multiple spatial resolutions. To obtain a 20-cm resolution DEM, bilinear interpolation was applied to downscale the SRTM data, as this resolution has been shown to reduce elevation gain measurement errors (Sánchez et al., 2024).

For each course and resolution, we then computed horizontal distance, elevation gain, elevation loss, km-effort, and fractal complexity using the criteria explained in the previous section.

To explore the impact of course resolution on km-effort, distance, and elevation gain, we performed a graphical analysis. This analysis contrasts, for each course, the relationship between course spatial resolution and km-effort, distance, and elevation gain, each measure presented in separate subplots. Rather than displaying total km-effort (or distance or elevation gain), the graphical analysis shows the relative measure compared to the 1-metre standard. At each resolution, the relative measure then reflects the proportion of the 1-metre standard captured at that resolution. To make the results more accessible, only the five races from the final UTMB event, which start and/or finish in Chamonix, France, will be highlighted in the charts for improved readability and clarity.

2.3. Evaluating the impact of 1-metre spatial resolution on ITRA's race categorisation system

To evaluate the effect of 1-metre spatial resolution on ITRA's race categorisation system, each course's km-effort scores and classification—calculated using both raw course data and the 1-metre standard—were compared through graphical analysis.

3. Results

3.1. Variation in spatial resolution across the UTMB circuit

Table 1 presents descriptive statistics for the 34 UTMB circuit courses included in this study, providing the mean, standard deviation, minimum, first quartile (q1), median (q2), third quartile (q3), and maximum values for the following variables: distance, elevation gain, elevation loss, km-effort, course resolution, fractal complexity, idle time, elevation gain during idle time, and elevation loss during idle time.

The average course resolution is 14.9 m, with the variability across events ranging from 1.9 m to 39.7 m. As a result, the fractal complexity, which measures geometric complexity, has a mean value of 1.18, with a range between 0.68 and 1.38. Most races exceed 100 km in distance, with an average race distance of 129 km. Elevation gain and loss are approximately symmetric, with average values around 6900 m, as indicated by the similar distributions across all quantiles.

In terms of data quality and course measuring protocols, 25% of the courses show that the average time spent stationary (idle time)—when the person measuring the track was not moving—exceeds 2.5%, with one extreme case reaching 24%. During these idle periods, elevation gain is typically minimal, with the third quartile (Q3) value being just 1 meter. However, an extreme case recorded 688 metres of elevation gain during GPS inactivity, likely due to measurement pauses and sensor recalibration, underscoring the potential for inaccuracies in such conditions.

3.2. Differences in kilometre-effort, distance, and elevation gain across spatial resolutions

Figure 1 shows the first 5 km of the UTMB 170-km course in Chamonix, France, the main event of the circuit. In this example, the horizontal frequency of GPS measurements was resampled to various resolution values, using the minimum, first quartile (q1), median (q2), third quartile (q3), and maximum values observed in the previous section, rounded to the nearest meter, as well as a 1-metre standard. As a result, the measured distance decreased from 4998 m, when using the 1-metre standard, to 4867 m, representing a shortening of the measured running distance by 2.62%. Additionally, as resolution decreased, both the distance and the number of vertices decreased, and the fractal complexity, which reflects the geometrical complexity of the course, was also reduced. This pattern aligns with the changes in resolution observed in the descriptive statistics.

Figure 2 displays three panels showing the relationship between horizontal resolution and km-effort, distance, and elevation gain for course resolutions ranging from 0.2 m to 100 m, calculated for all 34 courses on the UTMB World circuit. Down-sampling these courses leads to significant reductions in km-effort, distance, and elevation gain across all races. The most notable loss occurs in elevation gain, with certain courses losing up to 30% compared to a standard model with 1-metre resolution. Generally, the reduction in elevation gain ranges from 5% to 20% across most races. Reductions in measured horizontal distance are less dramatic than those in elevation gain but still significant. Races like TDS and UTMB show reductions of 3-4%, while other courses can lose up to

6.5% of their length. Most of the courses presented here experience a reduction in km-effort of more than 5% when compared to the standard 1-metre measurement. When the resolution is below 1 meter km-effort, distance and elevation gain continue to increase, but the growth rate is much slower than above 1 meter.

3.3. Impact of 1-metre spatial resolution on ITRA's race categorisation System

Figure 3 compares race classification and km-effort across all races using two protocols: raw original data and data processed at a 1-metre resolution. The results demonstrate the impact of resolution standardisation on race categorisation. While most races remain in their original categories, some shift to a different category when recalculated at the 1-metre standard, emphasizing the significance of standardisation. None of the five UTMB final event races—highlighted in this figure and the previous one—change categories, though subtle variations in their km-effort are evident. Races measured at higher resolutions typically show minimal changes in km-effort, indicated by horizontal lines between the protocols.

4. Discussion

The findings of this study reveal the profound impact of spatial resolution on the accuracy of races on natural terrain, such as trail and mountain running course measurements, carrying significant implications for the sport's ranking systems, race classification systems, performance comparisons, and overall development. By addressing the influence of resolution on key metrics such as distance, elevation gain, and kilometre-effort (km-effort), this study provides a critical foundation for standardizing measurement practices in events held on natural terrain courses.

The variability inherent in natural terrains, characterized by fractal complexity, exacerbates the challenges of accurate measurement. Coarse GPS resolutions, such as the average 14.9 metres observed in this study, fail to capture the human-scale details of rugged terrains, leading to significant underestimations of both distance and elevation gain. These inaccuracies, in turn, distort km-effort values, which are crucial for race classification and athlete benchmarking. For example, races measured at coarser resolutions experienced reductions in km-effort exceeding 5%, with some courses losing up to 30% of their elevation gain. Such discrepancies highlight the limitations of current measurement practices and the urgent need for a standardized approach.

The adoption of a 1-metre spatial resolution as a standard emerges as a solution (Li 2014). This resolution aligns with the level of detail required to accurately represent natural terrain courses at a human-scale, mitigating the distortions introduced by the fractal nature of the terrain. Resampling data to this resolution not only enhances the precision of key metrics but also provides consistency across events, allowing for meaningful comparisons between races and athlete performances. For instance, recalculating km-effort at a 1-metre resolution revealed shifts in race rankings and classifications, emphasizing how inconsistencies in measurement practices can affect the perceived difficulty of events and the integrity of competitive benchmarks.

Unexpected findings, such as elevation gain discrepancies during idle time, further illuminate the inconsistencies in current GPX data recording protocols. These variations show the need for standardized criteria in GPX files to ensure data cleanliness and reliability. Additionally, while some courses exhibited minimal changes when recalculated at a 1-metre resolution, others showed substantial shifts, pointing to the influence of both terrain complexity and device accuracy on measurement outcomes.

Despite its contributions, this study is not without limitations. The reliance on publicly available GPX files introduces variability in data quality, and while rigorous interpolation methods were applied to enhance resolution, these cannot fully replicate the precision of real-time high-resolution measurements. Additionally, the focus on UTMB races, while providing valuable insights into one of trail and mountain running’s most prominent circuits, may limit the generalizability of findings to other contexts. Future research should expand to include a broader range of events and terrain types, as well as field-based validations of GPS and elevation measurement methodologies.

The implications of this study are far-reaching. For elite runners, where performances are often separated by narrow margins, the measurement errors associated with inconsistent resolutions could influence rankings and performance indices such as the

ITRA index. For instance, the performances of the 1st and the 5th runner at UTMB 2024 lie less than 5% apart in terms of time (UTMB, 2024). If km-effort translates linearly into time spent running, this means that, when comparing efforts performed on two courses with theoretically equal distances, but different GPS measurement intervals, the difference in performance of the 1st and the 5th runner at UTMB could potentially lie within the margin of error occurring due to different measurement standards for two different events with equal distances. This standardization may not be relevant for two runners performing in the same race, but it becomes significant when comparing performance indices such as the ITRA index across different races, varied landscapes, and even different editions of the same race—especially as trail and mountain running events often feature minor course modifications every year.

The implications of this study extend beyond trail and mountain running. The standardization of distance and elevation gain measurements is equally applicable to other locomotion sports, such as cycling, hiking, skiing, and rowing, among others. These disciplines encounter similar challenges related to GPS variability, barometric recalibration, and the lack of standardized measurement protocols. Implementing approaches like those proposed in this study could significantly improve measurement accuracy and ensure comparability across events in a wide range of sports.

Conclusion

The adoption of a 1-metre resolution standard for measuring the distance and elevation gain of TMR courses would enhance the reliability and accuracy of natural terrain running sports, enabling consistent race classification, and facilitating scientific research on athlete performance in natural environments. Such advancements are essential for the development of sports such as trail and mountain running as a globally recognized discipline with robust benchmarks and reliable metrics.

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Table 1: Descriptive statistics for all 34 GPX files, including mean, standard deviation (±), [minimum, first quartile (q1), median (q2), third quartile (q3), maximum] values for distance, elevation gain, elevation loss, km-effort, course resolution, fractal complexity, idle time, elevation gain during idle time, and elevation loss during idle time.

Variable	Descriptive Statistics
Distance (kms)	129 ± 45 [38, 100, 123, 161, 258]
Elevation gain (m)	6879 ± 2883 [2436, 5058, 6312, 8692, 15652]
Elevation loss (m)	6981 ± 2972 [1894, 5041, 6667, 9236, 15655]
Km-effort	198 ± 69 [62, 158, 184, 237, 414]
GPS resolution (m)	14.9 ± 9.4 [1.9, 8.2, 14.2, 21.1, 39.7]
Fractal complexity	1.18 +- 0.13 [0.68, 1.15, 1.19, 1.24, 1.38]
Idle time (%)	2.3 ± 4.91 [0, 0.02, 0.16, 2.49, 24.85]
Elevation gain during idle time (m)	32 ± 122 [0, 0, 0, 1, 688]
Elevation loss during idle time (m)	-5 ± 13 [-66, -1, 0, 0, 0]

Figures:

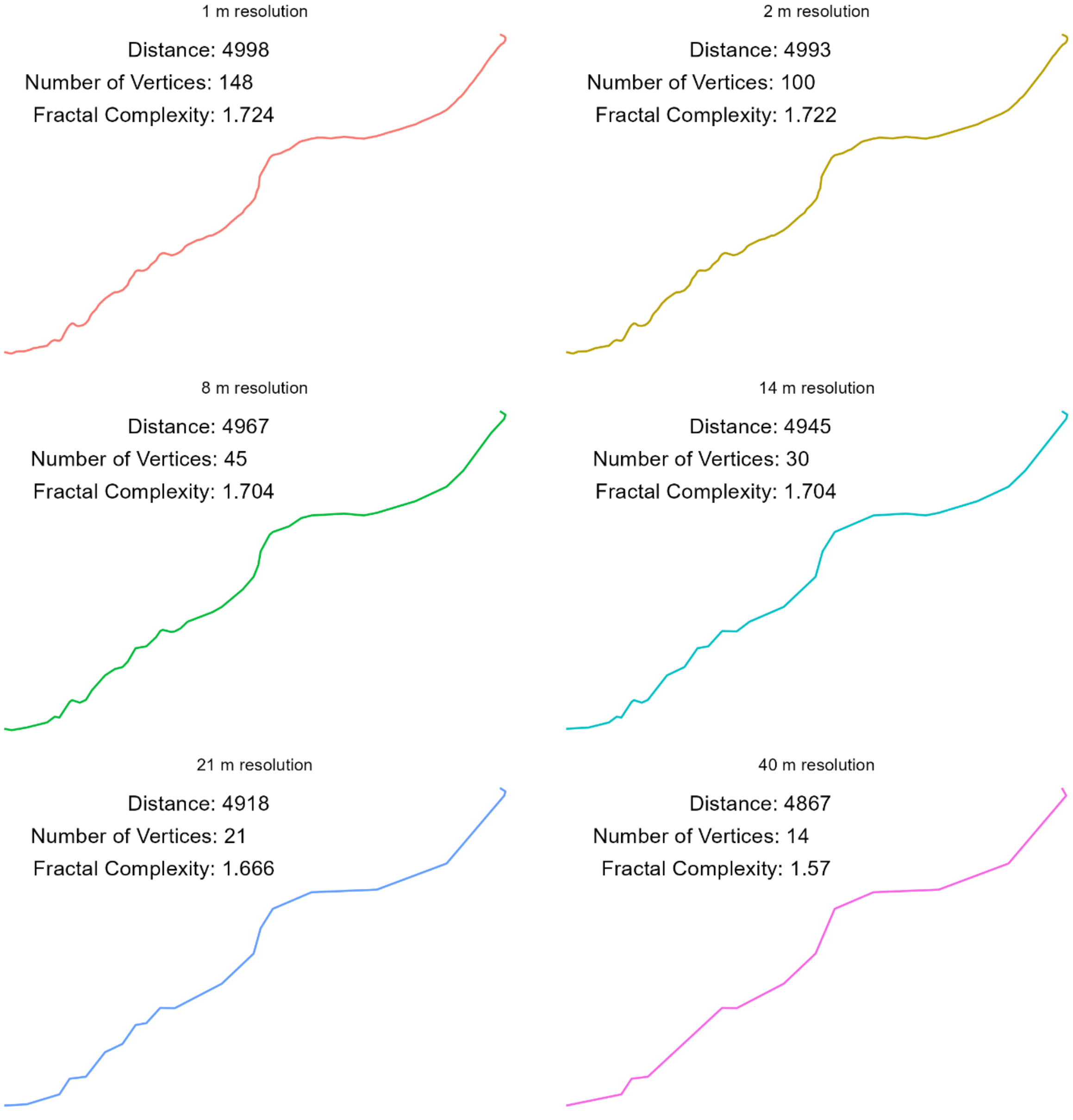

Figure 1: Stylized map displaying the first 5 km of the UTMB final event in Chamonix, France, at different GPS measurement resolutions.

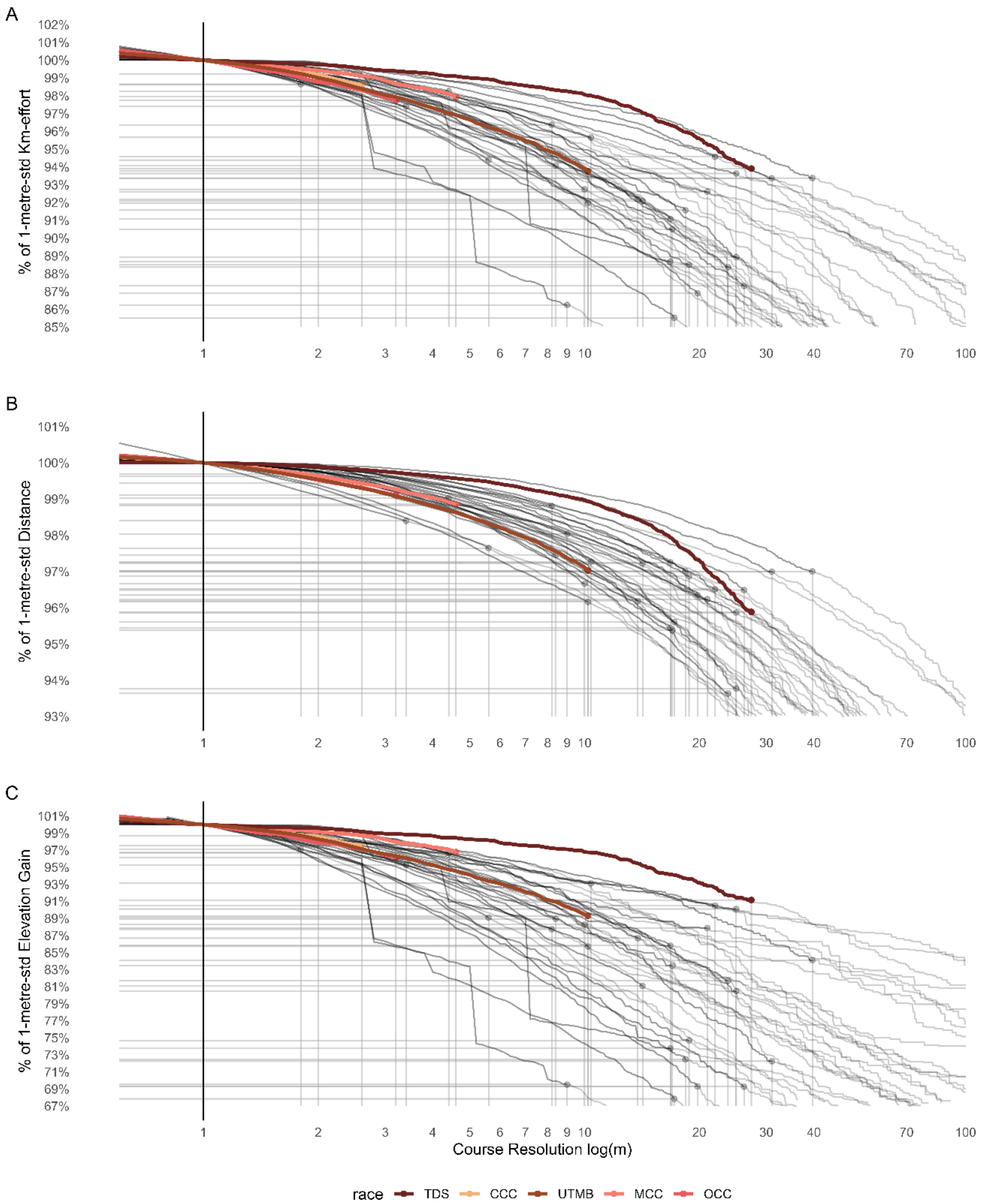

Figure 2: Relationship between course resolution and (A) km-effort, (B) distance, and (C) elevation gain, shown as percentages relative to the 1-metre standard. The plots illustrate how total km-effort, distance, and elevation gain decrease as resolution becomes coarser. A vertical black line at 1-metre resolution marks the reference point where all curves intersect the 100% value on the vertical axis. Races from the main UTMB event are labelled and highlighted in colour, while other UTMB World Series races are represented by grey lines.

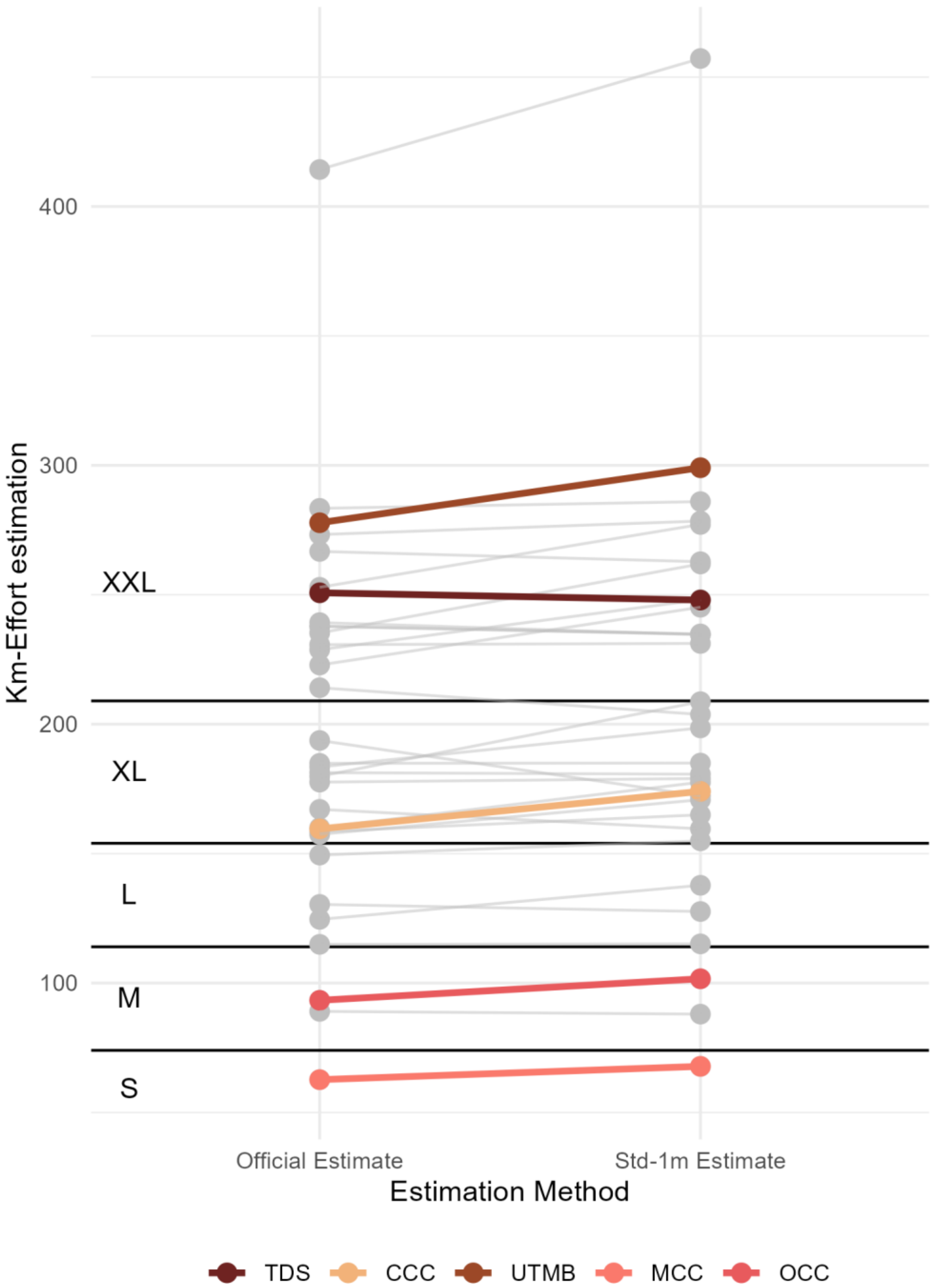

Figure 3: Comparison of km-effort scores between the original course data and standardized 1-metre resolution data, highlighting shifts in race classifications. The horizontal lines represent the thresholds for category changes, based on km-effort. Races of the main UTMB event are labelled and highlighted in colour, while other races in the UTMB World Series are depicted as grey lines.