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Rockfall hazard assessment by coupling three-dimensional, process based models and field-based tree-ring data

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A realistic evaluation of the spatial and temporal patterns of rockfalls is fundamental for the management of this very common hazard in mountain environments. Process-based, three-dimensional simulation models are nowadays capable to reproduce the spatial probability of rockfalls with reasonable accuracy through the simulation of numerous individual trajectories on highly-resolved digital terrain models. At the same time, however, simulation models typically fail to quantify the real frequency of rockfalls. The analysis of impact scars on trees, in contrast, yields empirical rockfall frequencies but, trees may not be present at the location of interest and rare trajectories may not necessarily be captured due to the limited age of forest stands on rockfall slopes. In this article, we demonstrate that the coupling of modeling with tree-ring techniques may overcome the limitations inherent to both approaches. Based on the analysis of 64 cells (40 $\times$ 40 m) of a rockfall slope located above a 1631-m long road section in the Swiss Alps, we illustrate results from 488 rockfalls detected in 1260 trees. We illustrate that tree impact data cannot only be used (i) to reconstruct the frequency of rockfalls for individual cells, but that they also serve (ii) the calibration of the rockfall model Rockyfor3D, as well as (iii) the transformation of simulated trajectories into real empirical frequencies. Calibrated simulation results are in good agreement with empirical rockfall frequencies and exhibit significant differences in rockfall activity between the cells (zones) along the road section. Empirical frequencies, expressed as rock passages per meter road section, also enable quantification and direct comparison of the hazard potential between the zones. The contribution provides an approach for hazard zoning procedures that complements traditional methods with a quantification of rockfall frequencies through a systematic inclusion of impact records in trees.