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Seasonal nitrate leaching pulses in the subtropical red soil critical zone

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Deep nitrate leaching pulses in agricultural landscapes remain poorly understood, owing to the challenges in obtaining time-resolved measurements of nitrate concentrations, isotopes, and deep drainage fluxes beyond the root zone. In this study, we quantified these pulses in a humid subtropical red soil critical zone using four years of high-frequency data on ion concentrations and dual nitrate isotopes across rainwater, streamwater, soil water, and groundwater, combined with modeled drainage at 200 cm depth. Our results reveal seasonal leaching pulses during the rainy season, synchronized with nitrogen fertilizer applications. The estimated annual leaching flux at 200 cm was 87.54 ± 24.28 kg N ha^{-1} yr^{-1}, representing 23% of total nitrogen inputs. The largest monthly leaching event accounted for 40–50% of the annual total, underscoring its pulsed nature. Of the nitrate leached below 200 cm, 16% accumulated in deep soil layers, while the remainder reached groundwater. Isotopic evidence further indicated denitrification in groundwater and streamwater, but not in soil water. These findings highlight the necessity of implementing precision nitrogen management strategies during monsoon periods to mitigate leaching losses in subtropical agroecosystems.