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Salinity and erosion: a preliminary investigation of soil erosion on a salinized hillslope

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Abstract This stu1dy aims to determine whether increasing soil salinity levels promote higher rates of runoff induced erosion. Rainfall simulation experiments, with an average intensity of 75 mm h^{-1}, were conducted on eight 1-m^2 runoff plots in central New South Wales, Australia. A cross-design method was adopted using three soil salinity levels (low, medium and high) and two vegetation covers (<10% and >30%). Multiple regression analyses reveal that the sediment concentration of runoff is positively related to soil salinity levels and negatively related to vegetation cover (R^2 = 0.688; $p > F$ = 0.048), suggesting a causal link between soil salinity and sediment mobilization. The results of this study will provide useful information to land managers seeking to redress salinity issues in terrestrial and aquatic ecosystems.

Key words electrical conductivity; hillslope erosion; rainfall simulation; runoff; salinization; soil erosion

INTRODUCTION

Dryland salinity has become a major land management issue in Australia and has dramatically expanded since European settlement. While Australian soils have naturally high subsurface salt levels, the replacement of salt-tolerant native vegetation by shallow rooted, less water intensive crops and the extensive use of irrigated agriculture has allowed local water tables to rise, causing salts to accumulate at the ground surface (Clarke *et al.*, 2002). As salinity levels increase plants find it difficult to extract water and nutrients from the soil and become susceptible to increased levels of toxic ions, such as sodium and chloride. Thus, salinized soils are unsuitable for many agricultural uses and exhibit reduced vegetation covers.

An additional and often less well recognized aspect of soil salinization is its multifactored influence on hillslope erosion (Rhoades, 1990). Salinized soils typically develop surface seals that form for two reasons: (1) sodium disintegrates soil aggregates and disperses clay particles, some of which become deposited in and subsequently block pore spaces; and/or (2) with their reduced vegetation covers, salinized soils are vulnerable to raindrop impacts that physically compact the ground surface (Singer *et al.*, 1982; Agassi *et al.*, 1994). Both of these processes lead to the development of surface seals that reduce infiltration, increase runoff and protect underlying soils from erosion (Shainberg & Singer, 1985). At the same time, however, the deflocculation of clay particles by sodium can increase the volume of loose material available for sediment transport by runoff, thereby increasing soil erosion rates (Agassi *et al.*, 1994). Thus, variations in soil salinity can have multiple competing effects on rates of runoff induced erosion.

Several authors have explored relations between soil salinity levels and hillslope erosion using laboratory analyses (for example, Singer *et al.*, 1982; Agassi *et al.*, 1994; Levy *et al.*, 1994; Mamedov & Levy, 2001; Mamedov *et al.*, 2002). These studies have generally concluded that soil salinity and erosion rates are positively related, indicating the importance of clay deflocculation as a sediment delivery mechanism. However, there is a need to test these findings on undisturbed soils in the field. Thus, the present study investigates links between soil salinity and hillslope sediment mobilization using rainfall simulations on an agricultural slope in central New South Wales, Australia. The objective of this part of the study is to determine whether increasing soil salinity levels generate higher rates of runoff induced soil erosion.

A second objective of this study is to consider whether salts contained in runoff contribute to the degradation of adjacent freshwater ecosystems. While dryland salinity has been associated with decreases in the health of adjacent rivers, most authors attribute in-stream salinity sources to groundwater inputs (for example, Nielsen *et al.*, 2003). Surface runoff, however, has the potential to transport and deposit substantive salt loads as both dissolved ions and saline sediments. Consequently, this study investigates the link between soil salinity and the salinity of runoff. These findings should improve our understanding of dryland salinity processes and provide valuable information for land mangers aiming to develop mitigation strategies that protect freshwater ecosystems.

METHODS

Links between soil salinity levels and runoff induced erosion were assessed using rainfall simulation experiments conducted on a hillslope adjacent to Bakers Swamp Creek, approximately 350 km northwest of Sydney, New South Wales, Australia (Fig. 1). The climate of the Bakers Swamp region is temperate, with a hot summer and no distinct dry season. Average annual rainfall at Wellington (Agroplow), approximately 23 km north of the field site, is 618 mm (± 185 mm) and mean monthly temperatures range from an average maximum of 32.8°C in January to an average minimum of 2.1°C in July.

The field work was undertaken in a region of low undulating hills comprising sedimentary (principally Early Silurian limestone) and volcanic rocks, with Quaternary alluvium deposits blanketing the intervening valley floor (Fig. 1) (Murphy & Lawrie 1998). The field site was positioned on an alluvial foot slope approximately 200 m from Bakers Swamp Creek with an average slope angle of 6%. The site has a patchy grass and thistle vegetation cover, is underlain by non-calcic brown soils and is actively grazed by sheep. A 2001 Salinity Investigation Brief (Wheeler 2001) reported soil electrical conductivity readings of 2–4 dS m^{-1} in the vicinity of the field site, indicating high soil salinity levels.

Rainfall simulation experiments were performed on eight 1 m^2 runoff plots (numbered 1–8) that were positioned across the field site (Fig. 1) to sample a range of vegetation covers (<10% and >30%) and soil salinity (EC_S) levels (<0.19 dS m^{-1} = low

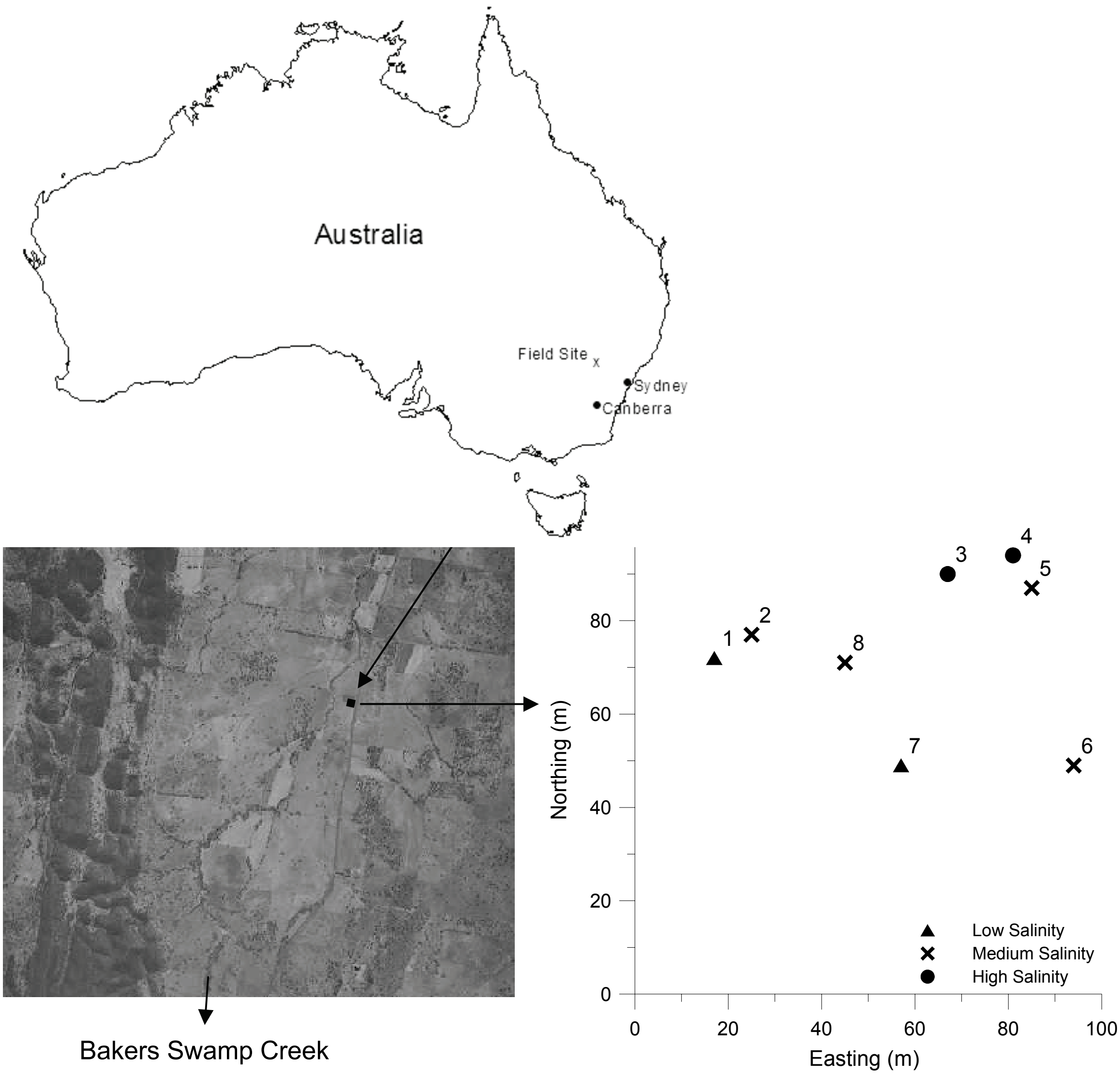

Fig. 1 Locations of the field site and the runoff plots. The soil salinity conditions of the runoff plots are based on the following classification: <0.19 dS m^{-1} = low salinity, 0.19–0.45 dS m^{-1} = medium salinity and >0.45 dS m^{-1} = high salinity (DNR Qld 1997).

salinity, 0.19–0.45 dS m^{-1} = medium salinity and >0.45 dS m^{-1} = high salinity) (DNR Qld 1997). Prior to the simulation events, percent cover for each plot was determined using a 1 m grid (divided into 10 cm units) that was placed over the plot surface. Each point within the grid was classified as either vegetated or unvegetated, providing a sample of 100 points per runoff plot. Soil electrical conductivity (EC_S) was analysed using a 1:5 soil water extract method. Soil samples collected at 5 cm depths were air dried and mixed with five parts distilled water. The electrical conductivities of the soil water mixtures were then measured using a portable conductivity meter. To avoid disturbing plot surfaces soil electrical conductivity (EC_S) readings were taken around the edge of each plot.

The rainfall simulators were based on the design of Luk *et al.* (1986) and generated precipitation at an average intensity of 75 mm h^{-1}. Each rainfall simulation event ran for 30 minutes during which timed runoff samples were collected at the plot base. The water used in the rainfall simulations was derived from a rainwater tank and recorded a very low *EC* (0.01 dS m^{-1}). At the completion of a rainfall event, the electrical conductivity of each runoff sample (EC_W) was measured using a portable electrical conductivity meter calibrated such that the *EC* of the rainwater was set to zero. In addition, the timed runoff samples were analysed in the lab using gravimetric techniques (weighing, drying and reweighing the runoff samples) to calculate discharge (Q), water yield (W_Y) and sediment concentration (S_C) for each runoff event. Links between soil salinity (EC_S) and runoff induced erosion were then assessed using regression and multivariate analyses.

RESULTS AND DISCUSSION

Surface property and runoff data for each plot are presented in Table 1. Runoff from plots under simulated rainfall typically exhibited the following responses: discharge (Q) increased until attaining equilibrium while sediment concentration (S_C) and electrical conductivity (EC_W) decreased throughout the flow event. Figure 2 depicts the typical form of these responses as illustrated by Plot 3.

Table 1 Runoff and surface property data for the eight plots used in the rainfall simulation experiments.

Plot	W_Y ($cm^3\ s^{-1}\ cm^{-2}$)	S_C (mg ml^{-1})	EC_S (dS m^{-1})	Cover (%)	pH	Soil Texture	OM (%)
1	0.0017	0.307	0.09	5	8.75	clay loam	8.48
2	0.0018	1.018	0.45	6	7.80	clay loam	7.88
3	0.0021	0.702	1.20	10	8.80	loam	10.25
4	0.0010	1.235	1.20	5	8.70	loam	9.90
5	0.0011	0.319	0.35	31	8.69	loam	14.58
6	0.0005	0.215	0.38	93	7.46	clay loam	15.44
7	0.0008	0.198	0.10	5	5.91	clay loam	12.17
8	0.0027	0.102	0.35	70	7.20	loam	34.59

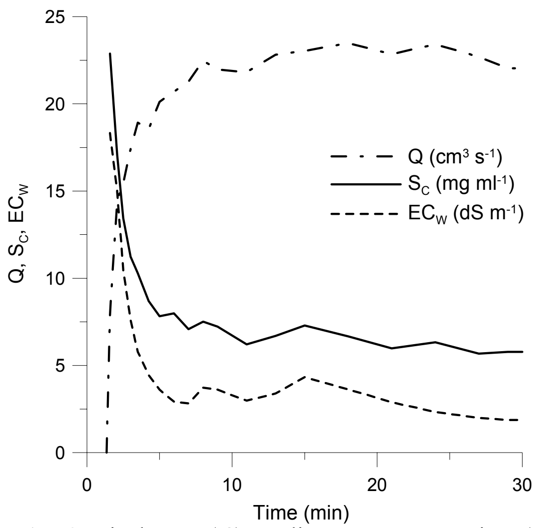

Fig. 2 Discharge (Q), sediment concentration (S_C) and electrical conductivity (EC_W) curves for runoff collected at the base of Plot 3.

The hydrological responses of the plots reflect the importance of infiltration in generating overland flow. At the beginning of a rainfall event, when soil moisture levels are at their lowest, infiltration rates are high and a substantial portion (if not all) of the moisture falling as rain is absorbed into the soil. As the rainfall event proceeds, however, pore spaces start to fill, infiltration rates decline and water accumulates on the soil surface—eventually generating overland flow (Fig. 2).

The declining EC_W and S_C rates reflect a combination of surface flushing, seal development and dilution effects. At the start of a rainfall event, loose soil and salt particles that have accumulated on the ground since the last rainfall event are readily entrained, generating initially high EC_W and S_C rates. As this early material is flushed out of the system, however, these available sources decline. At the same time, the rising discharge dilutes those sediments and salts that have been entrained/dissolved by the flows. Finally, surface seal development plays a dual role. Seals both increase soil cohesion, which helps to protect the ground surface from erosion, and they limit infiltration, which reinforces the rising discharge (Q) curve and enhances dilution effects.

Regression analyses between the runoff and surface property data disclose a positive relation between S_C and EC_S ($r^2 = 0.528$; $p > F = 0.041$) (Fig. 3; equation (1)) indicating that soil salinity levels promote runoff induced erosion:

$$S_C = 0.16 + 0.69EC_S \quad (1)$$

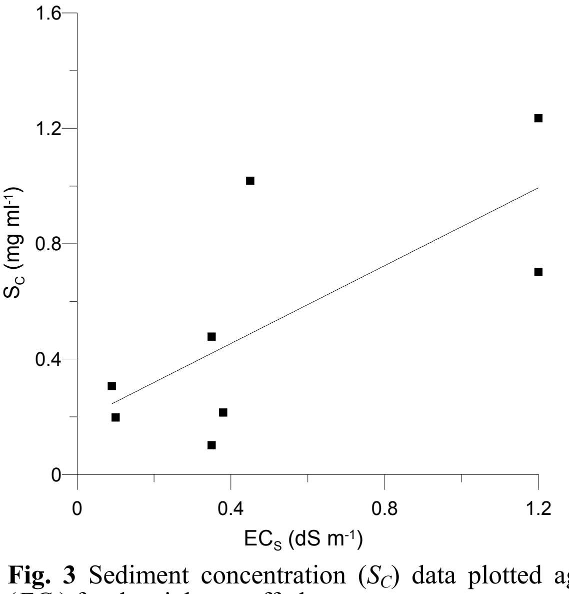

Fig. 3 Sediment concentration (S_C) data plotted against soil electrical conductivity (EC_S) for the eight runoff plots.

This outcome is consistent with earlier studies (e.g. Agassi *et al.*, 1994; Singer *et al.*, 1982) performed under laboratory conditions. The relation between S_C and EC_S reflects the role of soil salts as an agent of clay aggregate deflocculation. As clay aggregates are broken down, loose particles are made available for entrainment by runoff, increasing the concentration of sediment in the flow. Thus, rising soil salinity levels lead to increased sediment concentrations.

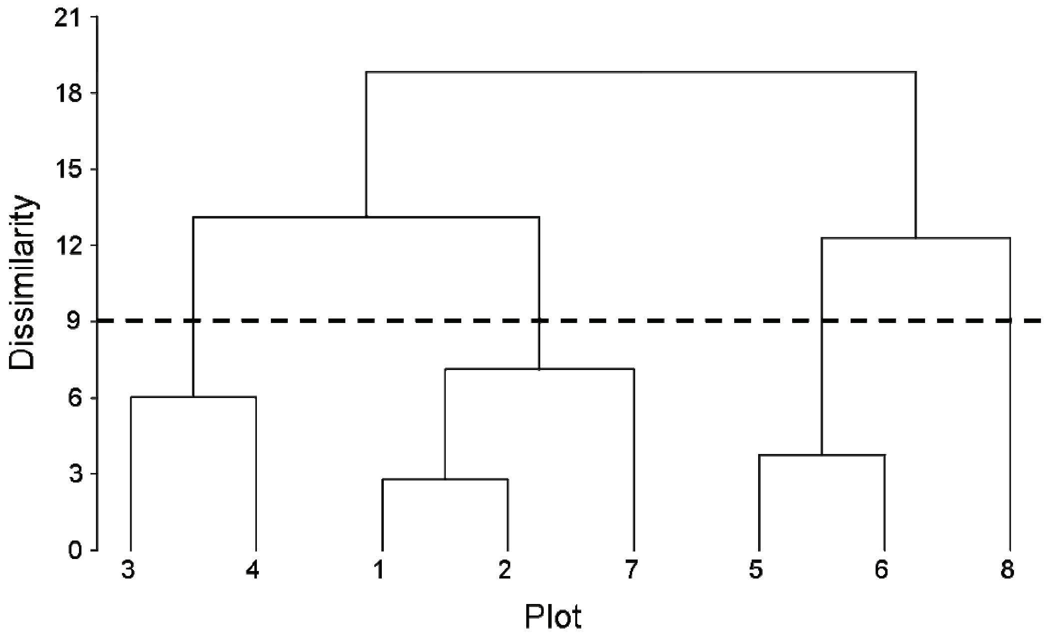

Fig. 4 A dendogram resulting from an agglomerative hierarchical classification of the runoff and surface property data utilizing Ward's method to define clusters based on dissimilarities. The dotted line represents the truncation point leading to the delineation of four groups. Group 1 includes the two high EC_S plots (3 & 4), Group 2 includes plots with <10%C (1, 2, & 7), Group 3 includes plots with >30%C (5 & 6), and Group 4 contains the only plot with a high OM (8).

Despite the statistical significance of equation (1), the comparatively low r^2 value suggests that EC_S is not the only factor contributing to variation in S_C. A multivariate approach was adopted to investigate whether other surface properties might be influencing sediment responses. Thus, the runoff and surface property data were used to derive an agglomerative hierarchical cluster of dissimilarities between plots (based on Ward's method) (Fig. 4).

Four clusters were delineated by this analysis that reflect between-plot differences in EC_S, %C and OM. Group 1 includes the high salinity plots (3 and 4); Group 2 includes plots with low %C and low to medium EC_S (1, 2 and 7); the Group 3 plots have high %C values (5 and 6); and Group 4 includes the only plot with a large OM value (8). These results indicate that vegetation cover is exerting an important influence on the runoff and erosion processes operating within this environment.

In response to the cluster analysis, therefore, a stepwise regression analysis was performed with S_C as the dependent variable and EC_S, %C and OM as the independent variables. The predictive power of the relationship presented in equation (1) was improved with the addition of percent cover (%C) as an independent variable. The multiple regression depicting this relationship has an R^2 = 0.688 ($p > F$ = 0.048) (equation (2)):

$$S_C = 0.34 + 0.61EC_S - 0.01\%C \quad (2)$$

While the inclusion of organic matter (OM) further improved the coefficient of determination (R^2) this relationship was not statistically significant at the 95% confidence level.

The importance of vegetation as a control on S_C can be explained in terms of its influences on infiltration and soil stability. Vegetation promotes infiltration by providing organic material that improves soil structure and by creating macropores. As infiltration rates rise, runoff volumes and, hence, shear stresses decline and the ability of the flows to erode and entrain sediment decreases. At the same time, roots bind soil particles together, making them more resistant to erosion. Thus, there is a negative relationship between S_C and %C (equation (2)).

The results of this study, therefore, indicate that soil salinity levels have both direct and indirect impacts on runoff induced erosion. The stronger of these two impacts is the direct influence of soil salinity on the deflocculation of clay aggregates which increases the availability of source material. However, soil salinity also indirectly influences erosion through its effect on vegetation cover. As soil salinity levels rise, vegetation covers decline and soils become increasingly vulnerable to runoff induced erosion.

The salinity levels of the runoff collected from the plots (EC_W) are presented in Fig. 5. All plots (except those with zero EC_W values) exhibit declining EC_W levels over time which is a consequence of dilution effects. For low EC_S plots there is no discernible relation between soil salinity level and EC_W. For medium and high EC_S plots, however, there is a significant transfer of salts from the soil surface to the runoff as expressed by the high EC_W values recorded for these plots. Importantly, EC_W values for the medium and high plots do not reach zero during the simulation events. This implies that salt sources on these plots are continuously available for entrainment throughout the runoff period.

The mobilization of salts by runoff has significant implications for the health of adjacent freshwater systems. Overland flows travel much faster than groundwater ensuring a more rapid transfer of saline water to riverine environments. In addition, there is the potential for sustained deliveries of material from soils with medium to

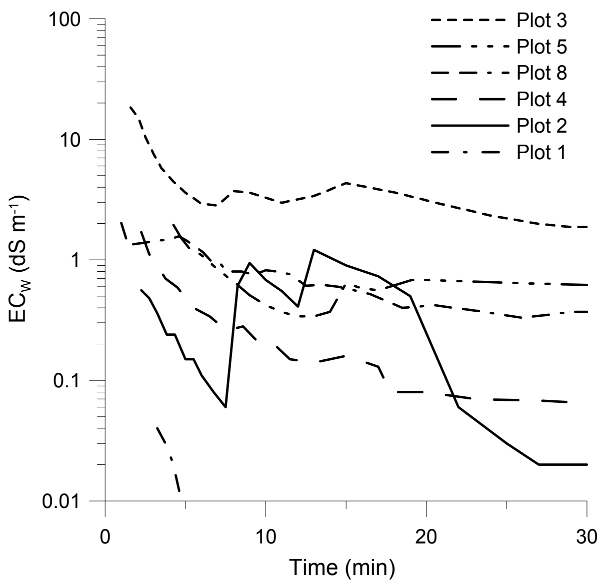

Fig. 5 Plot runoff electrical conductivity (EC_W) curves. Note: Plots 6 and 7 recorded zero EC_W values and, therefore, have not been included in this figure.

high salinity levels. Surface runoff, therefore, has the potential to contribute substantial salt loads to freshwater bodies and management initiatives need to address this. Soil salts will remain active sources of contaminants for as long as they are present on the ground surface.

CONCLUSIONS

Increasing levels of soil salinity in Australia have significant implications for terrestrial and aquatic ecosystems. Salinized slopes exhibit increased erosion rates under field conditions that result from the deflocculation of soil aggregates that provide loose soil for entrainment by overland flows. These findings confirm those of Singer *et al.* (1982), Agassi *et al.* (1994), Levy *et al.* (1994), Mamedov & Levy (2001), and Mamedov *et al.* (2002), who obtained similar results but under laboratory conditions. The extant vegetation cover also impacts on soil erosion from salinized hillslopes with higher vegetation covers reducing runoff sediment concentrations. However, surface cover was not as important as electrical conductivity in determining soil erosion rates. Thus, merely improving vegetation covers on saline slopes will not be sufficient to inhibit the elevated erosion rates that occur there.

Another important aspect of soil salinization is the increasing threat to freshwater ecosystems. Initially, salt free rainwater becomes highly saline after exposure to even moderate soil salinity levels. This rainfall, in the form of runoff, transports both ionic sodium and chloride into rivers but also transports saline soil particles which represent both short and long term pollutants to freshwater systems. It is likely that saline runoff and erosion from hillslopes represents a significant portion of the salt load delivered to freshwater ecosystems and, along with rising groundwater tables, poses a substantive risk to the health of these systems.

The results of this study highlight the need to actively manage salinized soils. The traditional approach of "fence and forget" does not address the longer term delivery of salts to freshwater systems. Only by an active rehabilitation strategy can the detrimental impacts of soil salinity be effectively mitigated.

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