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RESEARCH ARTICLE **(Open Access)**

Delineation of salinity management zones for precision irrigation in a salt-affected pomegranate orchard using DualEM-based remote sensing and Empirical Bayesian Kriging

ENDRIT KULLAJ[1*], EURORA MICI[1], XHULIO SEMA[1], ILIR KRISTO[1], EDWIN H. WINZELER[2], KABINDRA ADHIKARI[3], PHILLIP R. OWENS[4], ZAMIR LIBOHOVA[4*]

[1] Faculty of Agriculture and Environment, Agricultural University of Tirana, Albania

[2] Department of Mathematics, University of Texas, Arlington, Texas, USA

[3] Blackland Research & Extension Center, Texas A&M AgriLife Research, Temple, TX, USA

[4] USDA Agricultural Research Service, USA.

*Corresponding author; E-mail: zamir.libohova@usda.gov

Abstract

Soil salinity is a significant challenge for irrigated agriculture in low-lying coastal areas. Salts can vary greatly, even within a single orchard. This study tested a method to identify salinity management zones and develop a precision irrigation plan for a commercial pomegranate (*Punica granatum* L.) farm in Karavasta, Lushnja, Albania. The focus was on five parcels, covering about 50 hectares, within a 100-hectare salt-affected orchard on raised mounds. Researchers used satellite-derived salinity (NDSI, SI, SI3) and terrain attributes (MRVBF) for initial zoning. DualEM-1S electromagnetic induction sensor, a Delta-T W.E.T. field sensor were used in the field and electrical conductivity from soil-water extracts was determined in the laboratory for soil samples collected in the field. The DualEM readings were calibrated separately for raised mounds and inter-row spaces. Spatial patterns were mapped using Empirical Bayesian Kriging and regression-kriging methods. The results showed strong spatial variation in salinity, highlighting the clear differences between the raised mounds and the inter-row areas. The median electrical conductivity (EC) measured with the W.E.T. sensor was significantly higher in inter-row spaces than on raised mounds (862.0 versus 237.5 mS m^{-1}; $P = 0.002$), while soil moisture and temperature showed no significant difference. More than half of the inter-row area was classified as saline or highly saline, whereas most raised mounds were non-saline. The resulting maps were divided into five management zones, MZ-0 to MZ-4, each with different irrigation frequency, leaching fraction, and monitoring guidelines. This approach combined remote sensing, laboratory calibration, geostatistical mapping, and practical irrigation decisions, creating a useful framework for managing salinity in perennial orchards in Mediterranean coastal regions.

Keywords: soil salinity; precision irrigation; management zones; pomegranate; remote sensing; DualEM-1S; Empirical Bayesian Kriging

1. Introduction

Soil salinity reduces plant growth by increasing the osmotic potential of the soil solution and causing toxicities or nutrient imbalances that are specific to certain ions. In irrigated and coastal agricultural systems, salinity issues are often exacerbated by shallow groundwater, poor drainage, high evaporation rates, and the repeated use of irrigation water that contains varying salt levels. In Albania, salt-affected soils mainly occur in the western lowland, impacting tens of thousands of hectares. This includes areas where fruit trees, vegetables, forage crops, and field crops are grown. Salinity is especially critical in perennial orchards because establishing trees requires long-term investment. Management errors can also have lasting effects on soil structure, root-zone salinity, and tree productivity. Precision irrigation provides an opportunity to move from uniform water application to site-specific management based on soil and crop

*Corresponding author: Zamir Libohova; E-mail: zamir.libohova@usda.gov
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variability. In this context, management zones are sub-areas within a field that show comparable behavior in terms of soil properties, water availability, crop vigor or expected response to management. Management-zone delineation has been proposed for variable-rate irrigation and for irrigation scheduling because it can reduce water use while targeting areas where stress is more likely to occur [6,8,12]. However, in salt-affected orchards the irrigation decision is not driven only by crop evapotranspiration. It must also consider the leaching fraction required to keep salts below damaging thresholds, the quality of irrigation water, drainage conditions and spatial variability of salts in the root zone[2,3,7,17].

Electromagnetic induction and apparent electrical conductivity mapping have become useful tools for understanding soil variability and salinity patterns in fields. DualEM-type sensors allow for quick measurements of apparent electrical conductivity at various depths. These measurements can be compared with lab or field data on soil electrical conductivity. When paired with satellite images, soil salinity indices, and geostatistical methods, these measurements can create detailed maps that aid in decision-making. Remote sensing indices, such as the Normalized Difference Salinity Index (NDSI), Salinity Index (SI), and related brightness indices, are helpful for early identification of soil salinity issues. This is especially true when vegetation is sparse or when salt buildup influences surface reflectance.

Pomegranate is generally well-suited to Mediterranean environments, but irrigation practices, root-zone aeration, and salt stress can still impact its productivity and fruit quality[4,10,11]. The study orchard in Karavasta uses raised mounds to improve root-zone conditions in heavy, low-lying saline soils. This setup creates a natural contrast between the raised planting bed and the inter-row space. It also provides an opportunity to evaluate whether raised mounds lower salinity exposure and how high resolution salinity maps can be turned into practical irrigation choices. The goal of this paper was to: (i) identify salinity management zones using DualEM-based remote sensing, laboratory EC analysis, and Empirical Bayesian Kriging; (ii) compare salinity between raised mounds and inter-row areas; and (iii) develop salinity management zones for supporting precision-irrigation.

2. Material and Methods

2.1. Study Area

The study took place in a commercial pomegranate plantation run by Agro Iliria in Karavasta, Lushnja, Albania (Figure 1). This area is part of the Western Lowland region, known for its low elevation, proximity to the Adriatic coast, and heavy clay soils dominated by smectitic clays. The entire plantation spans about 100 hectares, while the detailed salinity mapping focused on five nearby parcels totalling around 50 hectares. The elevation of the agricultural parcels studied ranges from about -1.1 to 0.26 meters above sea level. Historically, the surrounding lowland has been a wetland that was converted into agricultural land in the 70s.

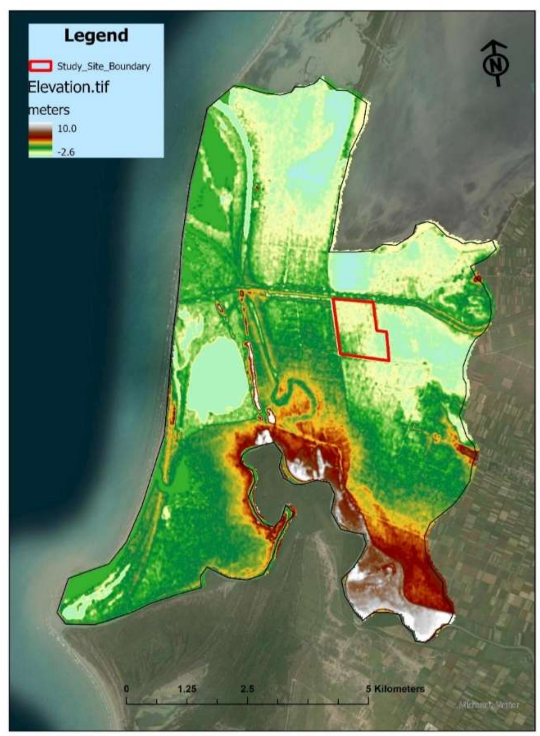

Figure 1. Location and elevation context of the study area in the Karavasta lowland, showing the plantation area within a low-lying coastal landscape

The orchard is planted on raised mounds, with open spaces between the planting beds. This system was created to improve rooting conditions, reduce waterlogging, and separate the active root zone from salt buildup in the lower parts of the field. The soils are both saline and heavy, making this site a suitable case for testing a management-zone approach in a high-value perennial crop under challenging soil conditions.

2.2. Remote-sensing stratification and salinity indices

A preliminary stratification of the orchard was created using satellite data and terrain information. We processed Landsat and Sentinel-2 data to derive indices related to salinity and combined them with terrain attributes such as Multiresolution Valley Bottom Flatness index (MRVBF) (Table 1). This index was calculated from elevation data at a 10 m grid resolution. We performed unsupervised ISODATA clustering in SAGA-GIS to find areas with similar spectral and terrain characteristics and to guide representative field sampling (Figure 2).

The indices used in the preliminary analysis included NDSI, SI, SI3, and related brightness or salinity indicators. We chose these indices because they highlight spectral differences linked to salt-affected surfaces. They also provide a low-cost way to identify possible salinity gradients before detailed proximal sensing.

2.3. Field sampling, proximal sensing and laboratory analysis

Field salinity measurements were collected from three sources: (i) a DualEM-1S electromagnetic induction sensor for quick soil sensing, (ii) a Delta-T W.E.T. field sensor for measuring soil electrical conductivity, moisture, and temperature at specific points, and (iii) laboratory electrical conductivity measurements from soil samples. Before mapping with the DualEM, we mowed selected inter-row strips to allow safe and consistent sensor movement between the orchard rows. We mounted the DualEM-1S sensor on a plastic sled and pulled it through the inter-row spaces using an all-terrain vehicle. A GPS unit recorded coordinates in real time, and saved the data through a rugged field tablet.

The DualEM-1S provided readings of apparent electrical conductivity that represent shallow and deeper soil layers. The study interpreted these layers as approximately 0-30 cm and 0-100 cm effective depths. For laboratory calibration, soil samples were taken from selected points at depths of 0-15 cm and 15-30 cm. In total, we collected approximately 300 soil samples for analysis. We measured laboratory electrical conductivity on a 1:5 soil-water extract, using 10 g of soil and 50 mL of distilled water. This was followed by shaking, centrifugation, and direct electrical conductivity measurement with an electrode. Field W.E.T. readings were taken on raised mounds and in the inter-row spaces to measure the differences between these locations.

Table 1. Main salinity and brightness indices used for preliminary stratification of the study site.

Index	Formula	Main purpose
NDSI	(Red - NIR) / (Red + NIR)	Highlights contrast between salt-affected and less affected surfaces
SI	sqrt(Blue x Red)	Empirical indicator of salt-affected bare soil surfaces
SI3	sqrt(Green^2 + Red^2)	Captures visible-band reflectance intensity related to surface salinity
BI	sqrt(Red^2 + NIR^2)	Brightness-related support variable
MRVBF	Terrain-derived index	Represents lowland flatness and water/salt accumulation tendency

2.4. Calibration, geostatistical mapping and validation

DualEM readings were calibrated against both laboratory EC1:5 measurements and field W.E.T. measurements. Calibration happened separately for raised mounds and inter-row spaces because the sensor response and salinity levels were expected to vary between these areas. The calibrated data were then used to create spatial maps of salinity across the five parcels.

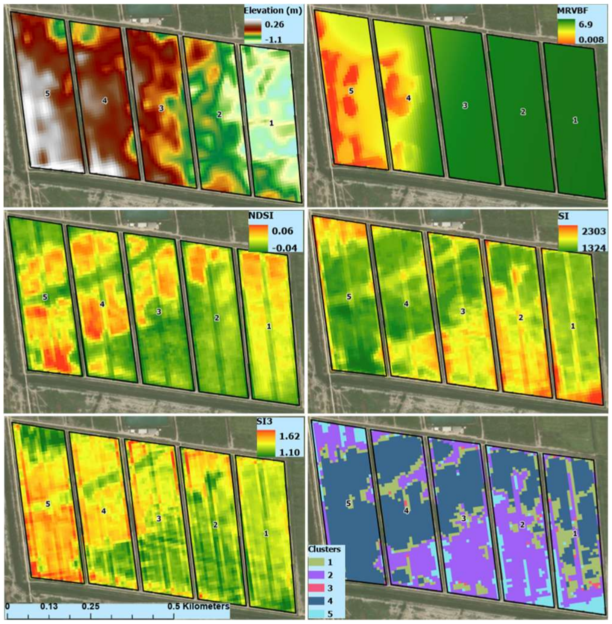

Figure 2. Example of spatial layers used for stratification: elevation, MRVBF, NDSI, SI, SI3 and preliminary clusters across the five study parcels

Empirical Bayesian Kriging (EBK) was used as the main interpolation method because it accounts for uncertainty in semivariogram estimation by simulating and combining multiple local semivariogram models. In general, the prediction at an unsampled location s_0 can be expressed as $z^*(s_0)$ = sum $w_i(s_0)$ $z(s_i)$, where $z(s_i)$ represents observed EC values and $w_i(s_0)$ are the kriging weights. Compared to a single global variogram, EBK is more effective when salinity patterns vary locally across an orchard. Leave one out cross validation was used by removing a single point from the dataset and using all remaining points to predict to the location of the point that was removed. The predicted values were compared to the measured values, based on (R^2, EMSE, RMSES) to determine the accuracy of the predictions.

2.5. Statistical analysis and management-zone translation

Descriptive statistics were calculated for EC measurements based on parcel, depth, and micro-position. Since EC values showed high variability and a non-normal distribution, differences between raised mounds and inter-row spaces were evaluated using a Mann-Whitney rank-sum test. Regression diagnostics assessed the strength of calibration relationships among laboratory, field, and proximal-sensing measurements.

The final salinity maps were divided into five management zones: MZ-0 (non-saline), MZ-1 (slightly saline), MZ-2 (moderately saline), MZ-3 (saline), and MZ-4 (extremely saline or critical). Each zone had a numerical salinity range, an indicative ECa range, and a main irrigation objective. The zones were used to adjust irrigation frequency, leaching fraction, and monitoring intensity.

3. Results and Discussion

3.1. Salinity contrast between raised mounds and inter-row space

The comparison of raised mounds and inter-row spaces showed that the raised-mound system significantly reduced salinity in the active planting area (Figure 3). The mean W.E.T. sensor EC was 1474.3 mS m^{-1} in the inter-row position, compared to 242.9 mS m^{-1} on the raised mound (Table 2). The median comparison confirmed this difference statistically: the median EC was 862.0 mS m^{-1} in the inter-row space and 237.5 mS m^{-1} on the raised mound (Mann-Whitney U = 242.5; P = 0.002). However, soil moisture and temperature did not show a significant difference between the two positions. This finding suggests that the EC difference was not just a result of short-term moisture or temperature variations during measurement.

This result is important for agriculture because the pomegranate root zone is mainly concentrated around the raised planting bed, while salts can accumulate in the lower inter-row space. The raised-mound system therefore helps reduce salinity. Nonetheless, the inter-row spaces are still crucial for diagnosis. They can indicate the overall salt load and the possible risk of lateral or upward salt movement toward the root zone if irrigation or drainage conditions are not appropriate.

3.2. Calibration and interpretation of DualEM-based salinity maps

DualEM-based proximal sensing captured the spatial structure of salinity across five parcels. The calibration results showed that the strongest relationships came from field W.E.T. EC readings and DualEM measurements (Table 3). This was particularly true on raised mounds, where the model using the shallow DualEM layer had R^2 = 0.93. Relationships with laboratory EC1:5 were weaker but still significant. This reflects the difficulty of matching point soil samples to the larger volume of electromagnetic induction measurements, along with the high spatial variability of salts in heavy saline soils.

The results support using DualEM data as a quick mapping layer, provided local calibration is performed. Laboratory EC remains important for confirming salinity levels, while the W.E.T. sensor serves as an intermediate field reference.

Table 2. Mann-Whitney Rank Sum Test median comparison results for measured EC, soil moisture and temperature based on a field probe.

Comparison	Raised mound	Inter-row space	Mann-Whitney statistic	P value
EC (mS m^{-1})	237.5	862.0	242.5	0.002
Soil moisture (volumetric fraction)	20.8	23.8	-3.1	0.533
Soil temperature (degrees C)	22.0	22.0	392	0.395

Table 3. Linear regression analysis summary (Equation; coefficient of determination- R^2 and root mean square error – RMSE) between Electric Conductivity (EC – mS m^{-1}) for the collected soil samples measured in the laboratory, by DUALEM and field sensors.

Comparison	Equation	R2	RMSE	Significance
Lab EC1:5 vs DualEM 0-30 cm	Log(Y)=2.51+0.37*Log(X)	0.31	1.02	P < 0.0001
Lab EC1:5 vs DualEM 0-100 cm	Log(Y)=0.52+0.83*Log(X)	0.40	0.96	P < 0.0001
W.E.T. EC inter-row vs DualEM 0-30 cm	Y=-184.1+3.63X	0.71	886	P < 0.0001
W.E.T. EC inter-row vs DualEM 0-100 cm	Y=104.2+3.84X	0.68	923	P < 0.0001
W.E.T. EC mound vs DualEM 0-30 cm	Y=213.5+0.06X	0.93	6.87	P < 0.0001

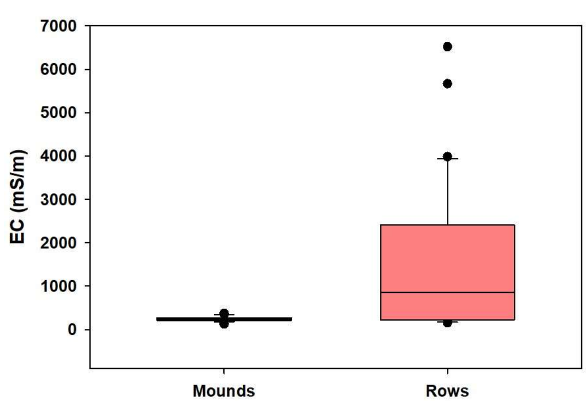

Figure 3. Difference in EC between raised mounds and inter-row spaces, showing the strong salinity contrast created by the raised-mound planting system

This combination is especially helpful where field variation is too large to be represented by a limited number of soil samples.

3.3. Delineation of irrigation management zones

The cross-validation results from the EBK showed high agreement with R^2 values between 0.93 and 0.99 and RMSE between 22.6 and 73.1 mS/m. The calibrated and cross-validated salinity maps (Figure 4) were converted into five irrigation management zones (Table 4 and 5). This step is important because a salinity map by itself does not guide irrigation decisions. Each zone was linked to a risk level and a management goal. These ranged from standard ET-based scheduling in non-saline areas to intensive monitoring, drainage checks, and leaching management in saline and critical zones.

The distribution of zones across the five mapped parcels showed significant variability within the orchard. About 23.4% of the mapped area fell into MZ-0, 17.2% in MZ-1, 18.6% in MZ-2, 22.5% in MZ-3, and 18.4% in MZ-4. Nearly 60% of the area was classified in the moderate-to-critical risk categories MZ-2 to MZ-4. Around 41% was in the high-to-critical categories MZ-3 and MZ-4. Parcel 2 had the largest area in MZ-3 and MZ-4, while Parcel 5 had the smallest critical area. These differences support planning irrigation at the parcel and zone levels instead of using one uniform schedule for the entire orchard.

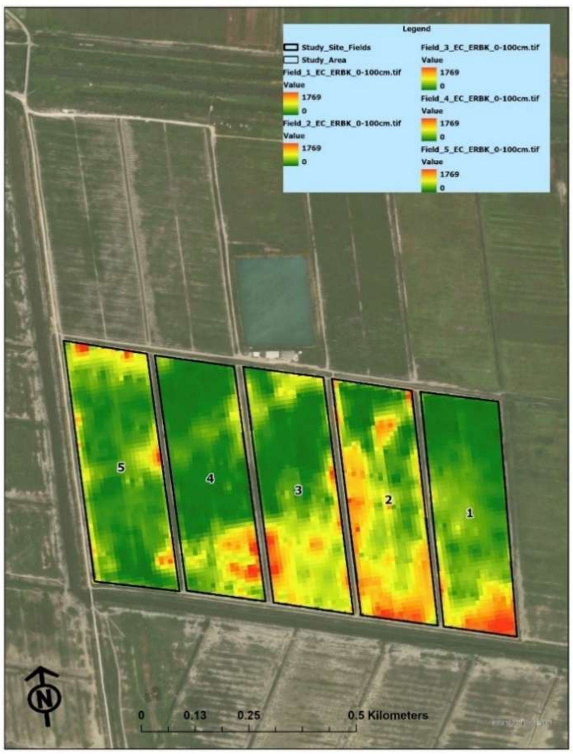

Figure 4. Example of DualEM-based EC interpolation for the 0-100 cm soil layer across the five parcels using the EBK-based mapping workflow.

3.4. Implications for precision irrigation and salinity control

The irrigation protocol created from the management-zone maps (Table 6) combines crop water needs, leaching fraction, and monitoring rules. In non-saline or slightly saline zones, irrigation can mostly follow standard crop evapotranspiration schedules with a modest preventive leaching fraction. In MZ-2, irrigation events should happen more often to prevent long dry spells, and the leaching fraction should be consistently included in seasonal planning. In MZ-3 and MZ-4, irrigation must include drainage checks, soil EC monitoring, and if needed, corrective actions like improving infiltration, widening the wetting pattern, avoiding high-salt fertilizers, or reassessing crop suitability.

For pomegranate, the main priority is to keep a good salt balance in the raised mound instead of trying to reclaim the entire area between rows. Field evidence shows that the mound system effectively protects the planting strip, but the surrounding salt reservoir should not be overlooked. A practical protocol should combine routine sensor readings in the mound, periodic soil sampling in both mound and inter-row positions, and seasonal map updates. Irrigation water ECw and sodium adsorption ratio (SAR) should be tested whenever the water source changes. If the root-zone ECe exceeds the target or rises quickly, irrigation frequency needs to be adjusted and the leaching fraction rechecked after 7-14 days.

This approach is also scalable. The same approach can be applied to other salt-affected orchards by adjusting the salinity classes to match local soil texture, water quality, and crop salinity tolerance. However, caution must be exercised when using satellite indices alone, as medium-resolution images may mix signals from soil, vegetation, and inter-row areas. For practical use, satellite data should serve as a screening layer, while DualEM, field EC sensors, and laboratory samples provide the calibration and validation necessary for management decisions.

Table 4. Operational translation of salinity classes into irrigation management zones

Map class	Zone	Indicative ECa range (mS m^{-1})	Risk interpretation	Significance
Non-saline	MZ–0	< ~299	Low risk	Standard ET scheduling plus modest preventive leaching
Slightly saline	MZ–1	~299–597	Emerging risk	Increase irrigation frequency and protect the raised mound
Moderately saline	MZ–2	~597–1194	High osmotic risk	Frequent irrigation plus structured leaching fraction
Saline	MZ–3	~1194–2388	Very high risk	Intensive leaching where drainage allows; strict monitoring
Extremely saline	MZ–4	> ~2388	Critical risk	Drainage and reclamation measures; irrigation alone is insufficient

Table 5. Area of the five parcels by irrigation management zone

Parcel	Area (ha)	MZ–0 (ha)	MZ–1 (ha)	MZ–2 (ha)	MZ–3 (ha)	MZ–4 (ha)
1	9.51	1.81	1.71	2.81	1.87	1.31
2	9.80	0.65	0.74	1.59	3.60	3.23
3	10.05	2.12	1.12	1.38	2.53	2.90
4	9.88	3.26	1.96	1.58	1.48	1.61
5	10.75	3.85	3.05	1.95	1.75	0.15
Total	49.99	11.69	8.58	9.31	11.23	9.20

Table 6. Generalized irrigation response by management zone

Zone	Target salinity control	Planning leaching fraction	Frequency rule	Monitoring priority
MZ–0	Prevent salt build-up	0.05–0.10	Standard ET-based scheduling	Routine seasonal EC checks
MZ–1	Early control	0.10–0.12	10-20% more frequent than MZ-0	Track ECe trend and mound protection
MZ–2	Managed salinity	0.12–0.18	High frequency; avoid long dry periods	Soil EC and vegetation stress confirmation
MZ–3	High restriction	0.18–0.25+	Daily or near-daily during peak ET if drainage allows	Hydraulic audit, drainage and ECe after leaching
MZ–4	Critical restriction	0.25–0.35+ only if feasible	Irrigation alone insufficient	Drainage, reclamation or land-use reassessment

4. Conclusions

The study showed that a combined workflow using satellite salinity indicators, DualEM-based remote sensing, laboratory EC analysis, and Empirical Bayesian Kriging can identify important salinity management zones in a salt-affected pomegranate orchard. The difference between raised mounds and inter-row spaces confirmed that raised mounds are a useful mitigation structure, but salinity is still very uneven throughout the orchard, dynamic over time and can reach deeper soil layers.

The five-zone classification, MZ-0 to MZ-4, serves as a practical link between spatial data and irrigation choices. About 60% of the mapped area fell into moderate-to-critical salinity risk categories, suggesting that uniform irrigation is probably not the best approach. Instead, irrigation scheduling should vary by zone, with increased monitoring intensity, irrigation frequency, and lea--ching fraction as salinity risk grows. In the most saline zones, irrigation strategies must also include drainage assessment and reclamation efforts.

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