

Application of a Time-Segment Corrected Dual-Source Model in Simulating Maize Evapotranspiration in the Arid Region of Northwest China: Postprint

Authors: Wu Lin, Leilei Min, Shen Yanjun, Zhou Xiaoxu, Liu Fenggui

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Abstract

Evapotranspiration (ET) constitutes an important component of terrestrial water cycle processes and serves as a critical link in regional energy and water balance. Accurate ET estimation is of great significance for improving water use efficiency and optimizing regional water allocation structures. This study utilizes observation data from the Heihe Major Program to compare canopy resistance models that consider versus ignore CO₂ concentration effects on maize canopy, couples them separately into the dual-source Shuttleworth-Wallace (S-W) model, and employs these two models to simulate ET at half-hourly scale by growth stage throughout the entire maize growth period. The models are validated using eddy covariance measurement data. Finally, sensitivity analyses are conducted separately on meteorological elements affecting maize canopy resistance and resistance parameters affecting ET, to explore patterns of farmland water consumption for maize at different growth stages in the oasis area of the middle reaches of the Heihe River under changing atmospheric CO₂ concentration conditions. The results demonstrate that after coupling the modified canopy resistance model considering CO₂ concentration effects on maize canopy into the S-W model, it can accurately simulate farmland water consumption processes at half-hourly scale for different growth stages throughout the entire maize growth period. Sensitivity analysis reveals that canopy resistance (c_{rs}) and aerodynamic resistance between canopy height and reference height (a_{ra}) exert the strongest influence on ET at each growth stage, while other resistance parameters have insignificant effects on ET. The magnitude of ET variation decreases with increasing c_{rs} and a_{ra} . The modified stage-specific dual-source model considering CO₂ concentration effects can accurately simulate ET at each growth stage throughout the entire maize growth period, and can provide a reference for farmland evapotranspiration research under conditions of planting structure

adjustment, land use pattern change, and CO₂ concentration variation.

Full Text

Simulation of Maize Evapotranspiration at Different Growth Stages Using Revised Dual-Source Model in Arid Northwest China

Wu Lin^{1,2}, Min Leilei², Shen Yanjun², Zhou Xiaoxu², Liu Fenggui^{1**}

¹College of Biological and Geographical Sciences, Qinghai Normal University, Xining 810000, China

²Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050022, China

Abstract

Evapotranspiration (ET), composed of vegetation transpiration (T) and soil evaporation (E), constitutes a critical component of the water cycle and plays a key role in regional energy and water balance. Accurate ET estimation is essential for improving water use efficiency and optimizing regional water allocation. Using observational data from the Heihe River Basin Program, this study compared two canopy resistance models—one incorporating atmospheric CO₂ concentration effects and one excluding them—coupled with the dual-source Shuttleworth-Wallace (S-W) model. The coupled models were used to simulate half-hourly ET throughout the entire maize growing period, with validation performed against eddy covariance measurements. Sensitivity analyses were conducted to examine how meteorological factors affect canopy resistance and how resistance parameters influence ET, aiming to elucidate water consumption patterns at different growth stages under altered atmospheric CO₂ conditions in the oasis region of the middle Heihe River Basin. Results demonstrate that the revised S-W model incorporating CO₂ effects on canopy resistance accurately simulated water consumption processes at half-hourly scales across all growth stages. Sensitivity analysis revealed that canopy resistance (r_c) and aerodynamic resistance from canopy to reference height (r_a) exerted the strongest influence on ET, with ET decreasing as these resistances increased. The stage-specific, CO₂-sensitive dual-source model provides a robust tool for estimating farmland ET under varying canopy structures, land use patterns, and changing atmospheric CO₂ concentrations.

Keywords: Shuttleworth-Wallace model; Evapotranspiration; Atmospheric CO₂ concentration; Resistance parameters; Maize

Introduction

Evapotranspiration (ET), comprising vegetation transpiration (T) and soil evaporation (E), represents a vital component of terrestrial hydrological processes and is fundamental to regional energy and water balance. Precise ET estimation is crucial for enhancing water use efficiency and optimizing regional water resource allocation. Stomata serve as the conduit for water-carbon exchange between plants and the atmosphere during ET processes, with their aperture controlled by both plant physiology and numerous environmental factors. Consequently, model simulation has become an effective approach for studying ET variation patterns and characteristics. Current ET models are primarily categorized as single-source, dual-source, and multi-source models, each introducing various resistance parameters to characterize soil evaporation and vegetation transpiration. Among these, canopy resistance—which describes the resistance water vapor must overcome when passing through the crop canopy—determines the accuracy of ET simulation.

The single-source Penman-Monteith (P-M) model, based on energy balance, treats the crop canopy and soil surface as a single entity, enabling ET estimation using partial meteorological elements and crop attributes. Numerous studies have indicated that the P-M model, based on the “big leaf” assumption, exhibits strong sensitivity to subsurface canopy properties and achieves high accuracy for fully-covered canopies but generates substantial errors during initial crop growth stages. In 1985, Shuttleworth and Wallace investigated ET from sparsely covered surfaces, introduced canopy and soil resistance parameters, and established a dual-source ET model comprising both crop canopy and understory components. This model has been widely applied due to its explicit consideration of soil evaporation and clear mechanistic basis. However, existing ET models have not accounted for atmospheric CO₂ concentration effects, despite CO₂ directly influencing water vapor flux exchange between crops and the atmosphere. Research demonstrates that elevated CO₂ concentrations reduce stomatal conductance, weaken crop transpiration, and induce stomatal closure, thereby significantly affecting ET and water use efficiency. Wand et al. found that doubled CO₂ concentration decreased stomatal conductance by 29% in C₃ crops, while Morison et al. reported a 40% reduction in field crops under doubled CO₂ scenarios.

Against the backdrop of global change characterized by rising temperatures and increasing atmospheric CO₂, elevated CO₂ and water scarcity have severely impacted regional agricultural sustainability. Current farmland ET research under climate change has not considered the synergistic effects of atmospheric CO₂ with other environmental factors. Therefore, incorporating CO₂ effects on crop ET is essential for revealing water consumption patterns and improving water use efficiency, particularly in water-limited regions. Existing canopy resistance parameters in ET models neglect CO₂ effects, yet for long-term model predictions—especially simulations of future climate and ecosystem water-carbon balance—accounting for CO₂ impacts on canopy resistance and ET becomes crit-

ical. Furthermore, crops exhibit distinct ET patterns across different growth stages; using a single parameter set to estimate ET for the entire growth period is unreasonable. Thus, stage-specific ET estimation combined with crop water consumption patterns at different phenological phases is necessary to improve simulation accuracy.

Based on Morison et al. and Easterling et al.'s research on CO₂ effects on stomatal conductance, this study utilized observational data from the Heihe River Basin Eco-Hydrological Process Integration Research Program. Building upon the dual-source Shuttleworth-Wallace model, we divided the maize growth period into three main stages, compared canopy resistance models with and without CO₂ effects for maize in the middle Heihe River oasis region, and coupled them into the S-W model to estimate transpiration and soil evaporation stage-specifically. After refining select resistance parameters and validating the model against eddy covariance measurements, we identified a canopy resistance model that reflects atmospheric CO₂ variation scenarios and explored farmland water consumption patterns across maize growth stages under changing CO₂ conditions.

1.1 Study Area

The middle Heihe River oasis is located in the central Hexi Corridor [Figure 1: see original paper], with elevations ranging from 1,131 to 2,891 m, covering the flat terrain from Yingluoxia (the river's mountain outlet) to Zhengyixia. The study area features a typical temperate continental climate with dry conditions and scarce precipitation (annual precipitation: 116.8 mm; annual evaporation: 2,365.6 mm) and severely uneven water resource distribution. Zonal soils consist of gray-brown desert soil and gray desert soil, while azonal soils include solonchak, fluvo-aquic soil, and aeolian sandy soil. Maize is one of the primary crops in this region, relying mainly on groundwater and Heihe River water for irrigation.

1.2 Data Sources and Processing

Observational data used in this study included automatic weather station measurements, flux data, and crop height data, all obtained from the Heihe Program Data Management Center (<http://heihedata.org/>). Meteorological variables measured by automatic weather stations comprised wind speed, wind direction, air temperature, precipitation, and humidity. Leaf area index (LAI) data were derived from NASA's MCD15A3H LAI product (<https://search.earthdata.nasa.gov/>), a 4-day composite L4 product at 500 m resolution, which was interpolated to daily scale using cubic spline interpolation with the assumption of constant LAI within a day. Flux data from Site 8 (100°22'35" E, 38°52'21" N; 1,550.06 m) were used for model parameterization, while data from Site 11 (100°20'31" E, 38°52'12" N; 1,575.65 m) and Daman station (100°22'20" E, 38°51'20" N; 1,556.06 m) served for model validation [Figure 1: see original paper]. All three stations observed throughout the

2012 maize growing season (early May to late September) from 9:00 to 18:30. Flux observation systems consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, USA) and an open-path CO₂/H₂O infrared gas analyzer (Li-7500A, Li-Cor Inc., USA) with a 10 Hz sampling frequency, outputting 30-minute averaged flux values. The underlying surfaces at all flux sites were maize with ridge spacing of 50.8 cm, row spacing of 43.3 cm, and plant spacing of 22 cm. Maize height was interpolated to half-hourly scale using cubic spline interpolation of measured data. Raw eddy covariance instrument information and data processing followed reference [30], including outlier removal, time delay correction, coordinate rotation, angle correction, and strict quality control. Additional processing steps included: (1) energy balance closure check—data with closure outside 0.5–1.5 were removed, while non-closed data were forced to close using the method in reference [31]; (2) data with latent heat flux (LE) < 0 W · m⁻², canopy resistance (r_{c}^{ob}) > 2,000 s · m⁻¹ or $r_{c}^{ob} < 0$ s · m⁻¹ were excluded (r_{c}^{ob} represents canopy resistance derived from the Penman-Monteith equation and defined as observed values).

The entire maize growing period was divided into three stages: (1) Early growth stage (June 6–July 20, 2012: sowing–emergence–five-leaf–jointing–tasseling–silking), characterized by rapid growth, increasing LAI, transition from sparse to dense ground cover, and shift from soil evaporation-dominated to transpiration-dominated ET; (2) Middle growth stage (July 21–August 31, 2012: silking–maturity), with complete ground cover, dominant transpiration, and diminishing soil evaporation; (3) Late growth stage (September 1–20, 2012: maturity–harvest), when maize matured, leaves senesced, stomatal conductance weakened, canopy resistance increased, transpiration declined markedly, and soil evaporation increased relative to the previous stage.

1.3.1 S-W Model

Shuttleworth and Wallace (1985) developed a dual-source ET model based on the P-M model for sparsely covered surfaces, introducing canopy and soil resistance parameters to represent crop canopy and understory components. The model is expressed as:

$$ET_{\lambda} = \lambda T + \lambda E = c_{PM} + s_{PM}$$

where ET_{λ} is total latent heat flux, comprising crop transpiration (λT) and soil evaporation (λE); c_{PM} and s_{PM} are canopy and understory latent heat fluxes (W · m⁻²) for calculating transpiration and soil evaporation, respectively; c_C and s_C are canopy and soil resistance partitioning coefficients; r_a^c is aerodynamic resistance from canopy surface to reference height (s · m⁻¹); r_a^s is aerodynamic resistance from ground surface to canopy height (s · m⁻¹); r_a^b is leaf boundary layer aerodynamic resistance (s · m⁻¹); r_s^c is canopy resistance (s · m⁻¹); Δ is the slope of saturation vapor pressure versus temperature (kPa · °C⁻¹); γ is the psychrometric constant (kPa · °C⁻¹); ρ is air density (kg · m⁻³); C_p is specific heat

of air at constant pressure ($\text{J} \cdot \text{kPa} \cdot ^\circ\text{C}^{-1}$); VPD is vapor pressure deficit (kPa); A is total available energy ($\text{W} \cdot \text{m}^2$); A_s is ground available energy ($\text{W} \cdot \text{m}^2$); R_n and R_{n_s} are net solar radiation above canopy and at ground surface ($\text{W} \cdot \text{m}^2$); G is soil heat flux ($\text{W} \cdot \text{m}^2$); c is extinction coefficient obtained through linear interpolation following references [4,8]; and LAI is leaf area index ($\text{m}^2 \cdot \text{m}^{-2}$).

1.3.2 Determination of Resistance Parameters

Aerodynamic resistance from canopy to reference height (r_a^c) and from ground surface to canopy (r_a^s) were calculated as:

$$r_a^c = \frac{\ln[(z-d)/z_0] \ln[(z-d)/Z_0']}{k^2 u_*}$$

$$r_a^s = \frac{h_c \exp(n)}{n K_h}$$

where k is the von Kármán constant (0.41); u_* is friction velocity ($\text{m} \cdot \text{s}^{-1}$); d is zero-plane displacement (m); h_c is mean canopy height (m); z is reference height (m); z_0 is roughness length (m); $Z_0' = 0.01$ m; K_h is turbulent diffusion coefficient within canopy ($\text{m}^2 \cdot \text{s}^{-1}$); n is turbulent diffusion attenuation constant (2.6) [31,32]; other parameters follow reference [33].

Leaf boundary layer aerodynamic resistance (r_a^b) and soil surface resistance (r_s^s) were calculated as:

$$r_a^b = \frac{r_b}{\text{LAI}}$$

$$r_s^s = r_{s,\min} \left(\frac{\theta_f}{\theta} \right)$$

where r_b is mean boundary layer resistance ($50 \text{ s} \cdot \text{m}^{-1}$) [35]; LAI is leaf area index ($\text{m}^2 \cdot \text{m}^{-2}$); $r_{s,\min}$ is minimum soil surface resistance ($100 \text{ s} \cdot \text{m}^{-1}$) [34,37]; θ is average soil water content in 0-100 cm depth ($\text{cm}^3 \cdot \text{cm}^{-3}$) [37]; and θ_f is average field capacity in 0-100 cm depth ($\text{cm}^3 \cdot \text{cm}^{-3}$).

Considering LAI, net radiation (R_n), soil available water content (θ), VPD, air temperature (T_a), and atmospheric CO₂ concentration effects on canopy resistance, we developed two canopy resistance models: one incorporating CO₂ concentration (r_s^{c1}) and one excluding it (r_s^{c2}) [38,39]:

$$r_s^{c1} = \frac{r_{s,\min}}{\text{LAI} \cdot f(R_n) \cdot f(\theta) \cdot f(\text{VPD}) \cdot f(T_a) \cdot f(\text{CO}_2)}$$

$$r_s^{c2} = \frac{r_{s,min}}{LAI \cdot f(R_n) \cdot f(\theta) \cdot f(VPD) \cdot f(T_a)}$$

where $f(R_n)$, $f(\theta)$, $f(VPD)$, $f(T_a)$, and $f(CO_2)$ are stress functions for net radiation, soil available water, VPD, temperature, and CO concentration, respectively. Minimum canopy resistance ($r_{s,min}$) was set to $20 \text{ s} \cdot \text{m}^{-1}$ for early and middle stages [40] and $294 \text{ s} \cdot \text{m}^{-1}$ for the late stage [41]. In the CO stress function, g represents the multiple of stomatal conductance reduction when CO concentration doubles (0.3) [29]. Field capacity (θ_f) was $0.34 \text{ cm}^3 \cdot \text{cm}^{-3}$ and wilting coefficient (θ_w) was $0.1 \text{ cm}^3 \cdot \text{cm}^{-3}$. Parameters a , b , and c are empirical coefficients requiring calibration.

1.4 Model Evaluation

Model performance was evaluated using coefficient of determination (R^2), mean bias error (MBE), and root mean square error (RMSE) to assess differences between simulated (E_m) and observed (O_{ob}) values:

$$R^2 = 1 - \frac{\sum_{i=1}^n (O_{ob,i} - E_{m,i})^2}{\sum_{i=1}^n (O_{ob,i} - \bar{O}_{ob})^2}$$

$$MBE = \frac{1}{n} \sum_{i=1}^n (E_{m,i} - O_{ob,i})$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (E_{m,i} - O_{ob,i})^2}$$

where E_m is simulated value, O_{ob} is observed value, \bar{O}_{ob} is mean observed value, and n is sample size. Observed ET (ET_{ob}) represents latent heat flux from eddy covariance measurements, while simulated ET (ET_m) denotes model outputs.

2.1 Model Parameter Calibration and Validation

Parameter calibration utilized Site 8 flux data (June 6-September 20, 2012), with nonlinear regression applied separately to early (June 6-July 20), middle (July 21-August 31), and late (September 1-20) growth stages using least squares method. Optimal parameter values are listed in Table 1, with model comparison results shown in [Figure 2: see original paper] and [Figure 3: see original paper]. Site 11 and Daman station data were used for model validation.

Table 1 Optimum parameters of the two canopy resistance models considering (r_s^{c1}) and non-considering (r_s^{c2}) CO concentration in three growing stages of maize

Growth stage	Model	a	b	c
Early growth stage	r_s^{c1}	-0.350	-0.335	-0.002
	r_s^{c2}	-0.264	-0.251	-0.038
Middle growth stage	r_s^{c1}	-0.350	-0.335	-0.002
	r_s^{c2}	-0.264	-0.251	-0.038
Late growth stage	r_s^{c1}	-0.350	-0.335	-0.002
	r_s^{c2}	-0.264	-0.251	-0.038

As shown in [Figure 2: see original paper] and [Figure 3: see original paper], both models (with and without CO effects) adequately captured ET variation patterns across growth stages during the calibration period. However, the CO-sensitive S-W model [Figure 2e: see original paper] achieved higher simulation accuracy, more realistically reflecting ET variation at each stage. The CO-insensitive model [Figure 3e: see original paper] overestimated mid-season ET, reducing overall simulation quality.

During the early stage [FIGURE:2a and 3a], rapid maize growth increased LAI and respiration, with ground cover transitioning from sparse to dense and ET shifting from evaporation-dominated to transpiration-dominated. This complexity reduced many models' performance, but the CO-sensitive S-W model [Figure 2a: see original paper] best captured ET responses to environmental variables. In the middle stage [Figure 2b: see original paper], abundant light, heat, and water intensified photosynthesis and CO demand, with complete ground cover focusing energy on dry matter accumulation. Transpiration dominated while soil evaporation diminished, creating relatively stable ET. The CO-sensitive model effectively represented this process, whereas the CO-insensitive model showed lower performance. In the late stage [Figure 2c: see original paper], maturing maize experienced rapid leaf senescence, reduced stomatal conductance, increased canopy resistance, and mechanical damage from parent plant removal, leading to weakened transpiration and enhanced soil evaporation. The CO-sensitive model [Figure 2c: see original paper] maintained high simulation accuracy.

Comparing entire growing season simulations at Site 8 [FIGURE:2d, 2e vs. 3d, 3e], the CO-sensitive model [Figure 2d: see original paper] outperformed the CO-insensitive model [Figure 3d: see original paper], with R^2 values of 0.96 versus 0.93, respectively, and lower RMSE and MBE. The CO-sensitive model showed only slight overestimation in the late stage [Figure 2e: see original paper], while the alternative overestimated ET throughout the season [Figure 3e: see original paper]. Thus, coupling the CO-sensitive canopy resistance model with the S-W model enables more accurate stage-specific ET estimation.

2.2 Further Model Validation

Both canopy resistance models were coupled with the S-W model to simulate ET at Site 11 and Daman station, with results shown in [Figure 4: see origi-

nal paper]-[Figure 7: see original paper]. At Site 11, both models performed reasonably well across growth stages, but the CO -sensitive model [Figure 4: see original paper] better captured ET variation, achieving determination coefficients of 0.96, 0.98, and 0.88 for the three stages, with an overall R^2 of 0.96 and minimal errors. The CO -insensitive model [Figure 5: see original paper] performed poorly in early and late stages ($R^2 = 0.95, 0.97$, and 0.64, respectively), underestimating ET throughout the season [Figure 5e: see original paper], particularly in middle and late stages when reduced light and temperature increased variability in transpiration and evaporation that the model could not rapidly track.

At Daman station, the CO -sensitive model [Figure 6: see original paper] effectively simulated ET across all three stages with high consistency ($R^2 = 0.98, 0.98$, and 0.94; overall $R^2 = 0.97$) and low RMSE and MBE. The CO -insensitive model [Figure 7: see original paper] underestimated early-stage ET and failed to capture peak values. Large variability in soil evaporation and transpiration during the late stage increased simulation errors ($R^2 = 0.97, 0.97$, and 0.80; overall $R^2 = 0.95$).

Collectively, [Figure 4: see original paper]-[Figure 7: see original paper] demonstrate that coupling the CO -sensitive canopy resistance model with the S-W model better simulates ET variation under changing physiological and meteorological conditions, accurately partitioning soil evaporation and transpiration with high consistency between simulated and observed values, particularly during early and middle stages. The model's easily obtainable parameters and good adaptability indicate its suitability for estimating ET in arid regions with low vegetation cover, addressing the large errors associated with P-M model applications under sparse canopy conditions.

2.3 Sensitivity Analysis

Due to variations in crop characteristics and external factors, model responses differ substantially across stages. We first analyzed sensitivity of canopy resistance to CO and other factors, then examined how resistance parameters affect the coupled S-W model. Sensitivity coefficient (S_{ix}) was defined as:

$$S_{ix} = \frac{\partial y/y}{\partial x_i/x_i}$$

where S_{ix} is the dimensionless sensitivity coefficient of model output y to variable x_i . Positive S_{ix} indicates output increases with variable increase, while negative values indicate inverse relationships. The magnitude reflects sensitivity strength.

First, canopy resistance (r_s^c) sensitivity to $\pm 10\%$ and $\pm 30\%$ changes in various factors was calculated. [Figure 8: see original paper] shows that during early [Figure 8a: see original paper] and middle [Figure 8b: see original paper] stages,

the most influential factors were net radiation (R_n), soil water content (θ), and LAI, followed by VPD, with temperature (T_a) and CO concentration being least influential. Sensitivity increased with perturbation magnitude. In the late stage [Figure 8c: see original paper], canopy resistance was most sensitive to θ and LAI, followed by R_n . During middle [Figure 8b: see original paper] and late [Figure 8c: see original paper] stages, CO concentration increases of 10% and 30% influenced r_s^c more than T_a .

Second, ET sensitivity to $\pm 10\%$ and $\pm 30\%$ changes in resistance parameters was analyzed [Figure 9: see original paper]. Throughout the growing season, canopy resistance (r_s^c) and aerodynamic resistance from canopy to reference height (r_a^c) exerted the strongest influence on ET, with other resistance parameters showing minimal effects. This influence was most pronounced in early [Figure 9a: see original paper] and late [Figure 9b: see original paper] stages. ET decreased as r_s^c and r_a^c increased, though this effect diminished with larger perturbations. Analysis reveals that r_s^c represents resistance to water vapor flow through stomata and leaf surfaces; increased r_s^c signifies greater resistance, reducing canopy conductance and suppressing water loss. Conversely, decreased r_s^c enhances canopy conductance, promoting transpiration and water consumption. Therefore, when applying the CO-sensitive, stage-specific S-W model, careful determination of r_s^c and r_a^c —the resistance parameters most affecting ET calculation results at different growth stages—is essential.

3 Conclusions and Discussion

Using observational data from the Heihe River Basin Program, this study compared canopy resistance models with and without CO effects, coupled them with the dual-source S-W model, calibrated parameters stage-specifically, estimated transpiration and soil evaporation, and validated the model against eddy covariance data. Key conclusions are:

- 1) Coupling the CO-sensitive canopy resistance model with the dual-source S-W model accurately simulated water consumption processes at half-hourly scales across all growth stages, with easily obtainable parameters and good adaptability.
- 2) Sensitivity analysis revealed that canopy resistance was most sensitive to R_n , θ , and LAI, and less sensitive to other meteorological factors. Resistance parameters affected ET differently across stages, with ET being most sensitive to r_s^c and r_a^c and insensitive to other parameters. Therefore, careful determination of r_s^c and r_a^c is critical when applying the CO-sensitive, stage-specific S-W model.

While the CO-sensitive canopy resistance model coupled with the S-W model accurately simulated stage-specific ET, the study was limited to three sites and short-term observations. Future work should incorporate more extensive and longer-term datasets to further refine CO effects on canopy resistance. Additionally, this study only considered CO effects on canopy resistance based

on previous research, without accounting for CO₂ impacts on LAI—an aspect requiring further improvement.

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