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EFFECTS OF WINDBREAKS, MULCHING AND REDUCED RUNOFF ON YIELD AND WATER PRODUCTIVITY OF THREE RAINFED CROPS

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Abstract: Rainfed crop production in eastern Austria is increasingly exposed to growing-season water deficits. Water retention measures can reduce unproductive water losses, but their relative effectiveness across crops is unclear. This study compared three measures and their combination for soybean, spring wheat and maize on the Marchfeld plain. AquaCrop 7.1 was run for 31 growing seasons (1995–2025) with daily climate data from Groß-Enzersdorf. The scenarios were a rainfed control (S0), a curve number reduction (S1), 75% organic mulch cover (S2), a 50% wind-speed reduction representing windbreaks (S3), and all three measures combined (S4). Curve number reduction changed mean yields by no more than 0.1%, because simulated surface runoff was very low. Wind-speed reduction was the most effective single measure. It raised mean yields by 20.5% (soybean), 14.8% (spring wheat) and 11.7% (maize). The combined scenario raised mean yields by 28.9%, 19.0% and 14.4%, and water productivity by 25–38%. In the driest season (2000), combined measures raised soybean yield from 0.84 to 2.01 t ha^{-1} and maize yield from 4.74 to 8.23 t ha^{-1}. A 30% wind-speed reduction still produced just over half of the benefit of the 50% reduction. Sheltering fields and combining evaporation-reducing practices may therefore lower the risk of severe yield losses on flat, drought-prone lowlands. Field validation is needed before the absolute gains can be generalised.

Keywords: AquaCrop; windbreak; mulching; curve number; water productivity; rainfed agriculture; agricultural drought; Marchfeld

INTRODUCTION

Water scarcity during the growing season is a growing constraint on European agriculture. Austria has warmed more than the global average since the late nineteenth century, and higher temperatures increase evapotranspiration and can reduce soil moisture even when precipitation remains unchanged (APCC, 2025). Droughts in Central Europe may become more frequent and severe as evapotranspiration increases and precipitation becomes more irregular (Spinoni et al., 2018). For rainfed crops the relevant form is agricultural drought, which occurs when soil moisture cannot meet crop water demand (Mishra & Singh, 2010). Agriculture accounts for over half of all drought-related losses in Europe, and annual drought-related losses in EU agriculture could rise from €4.8 billion in 2015 to €28.6 billion by 2100 without adaptation (ResAlliance, 2024).

The Marchfeld, a lowland region of about 1000 km² in northeastern Austria, is one of the warmest and driest parts of the country (Eitzinger et al., 2013). It belongs to the Pannonian climatic zone, with high sunshine, high growing-season temperatures and low precipitation (Moitzi et al., 2020), and is generally classified as semi-arid (Strauss et al., 2012). Because precipitation cannot meet evaporative demand, even small changes in soil-water availability strongly affect regional crop production (Eitzinger et al., 2013). Below roughly 1 m the loess-derived profile passes into sand and

gravel, and the groundwater table lies more than 3 m below the surface (Lalić et al., 2018). Regional assessments project yield declines of more than 50% for fields without irrigation (BAW, 2024).

Water retention measures reduce unproductive losses through soil evaporation and surface runoff, which remove a substantial part of the water available to crops in drought-prone systems (Bodner et al., 2015). No-tillage can reduce runoff and increase soil water storage in climates from humid to semi-arid (Dhakal et al., 2024), although a global meta-analysis found an average yield reduction of about 5%, with the best performance under rainfed conditions in dry climates (Pittelkow et al., 2015). Mulch reduces soil evaporation and maintains moisture in the root zone (Kader et al., 2017); a meta-analysis of 74 studies reported increases in yield and water-use efficiency of up to 60%, larger for maize than wheat and for plastic film than straw (Qin et al., 2015). Windbreaks reduce wind speed and evapotranspiration in their lee: near a hedgerow in eastern Austria wind speed fell by up to 34–41% and daily reference evapotranspiration by 0.6–0.7 mm d^{-1} (Gollobich et al., 2026), and in a sheltered vineyard reference evapotranspiration fell by 18.4% during the growing season (Veste et al., 2020). Percentage yield increases from shelterbelts tend to be higher in drier regions and years (Kort, 1988).

These measures have been studied individually in many settings. To the authors' knowledge, they have rarely been compared directly for several crops under a shared long-term climate, and no such comparison exists for the Marchfeld. AquaCrop is suitable for such a comparison because it separates productive transpiration from soil evaporation, converts transpiration into biomass through a normalised water productivity, and derives yield from biomass and harvest index (Steduto et al., 2009). It requires less input information than CropSyst and WOFOST while simulating biomass and yield with comparable accuracy (Todorovic et al., 2009).

This study compared three water retention measures — reduced surface runoff, organic mulching and a windbreak effect — applied individually and in combination to rainfed soybean, spring wheat and maize. It was hypothesised that (H1) the measures would increase yield and water productivity relative to the control, (H2) the combination would give the greatest improvement, and (H3) benefits would be greatest in drought years.

MATERIALS AND METHODS

2.1 Site and climate data

Daily climate data for 1995–2025 from the Groß-Enzersdorf station (48.20° N, 16.56° E; 153 m a.s.l.) were obtained from the GeoSphere Austria Data Hub (GeoSphere Austria, 2026). They comprised minimum, mean and maximum air temperature, precipitation, global radiation, wind speed and relative humidity. Precipitation values of −1, indicating no measurable precipitation, were set to 0, and missing daily values were filled by interpolation. Daily reference evapotranspiration (ETo) was calculated with the FAO Penman–Monteith equation (Allen et al., 1998).

Mean annual precipitation was 569 ± 106 mm and mean annual ETo 966 ± 70 mm. In the growing season (April–September) precipitation averaged 386 ± 92 mm against an ETo of 757 ± 54 mm, giving a mean water balance of −370 ± 125 mm. Over the 31 years, growing-season temperature increased by 0.58 °C per decade and growing-season ETo by 33.1 mm per decade (both $p \leq 0.001$, ordinary least squares regression), whereas precipitation showed no significant trend ($p = 0.90$).

2.2 Drought years

Drought years were identified from climate data. For each crop and year, precipitation and ETo were summed over the crop growing period (15 April–1 September for soybean, 22 March–29 July for spring wheat, 15 April–22 August for maize). The climatic water balance P − ETo was standardised to the 1995–2025 mean and standard deviation. Seasons with an index ≤ −1 were classed as drought years and those with an index ≤ −1.5 as severe. The year 2000 was the only severe season for all three crops and served as the reference drought year.

2.3 Soil and model set-up

The site soil is a calcareous grey alluvial soil formed from young fine alluvial deposits (Bodenkarte.at, 2026). Since the AquaCrop soil database contains only standard USDA texture classes, the profile was represented by the two nearest classes: sandy loam for soybean and spring wheat (field capacity 22 vol %, permanent wilting point 10 vol %, curve number 46) and silt loam for maize (33 vol %, 13 vol %, curve number 61). Hydraulic properties were derived by AquaCrop from the texture class (Raes et al., 2018). Maximum rooting depth was limited to 1 m, consistent with the transition to sand and gravel and the deep water table (Lalić et al., 2018).

AquaCrop version 7.1 (Raes et al., 2023) was used. Above-ground biomass is calculated as $B = WP^* \times \Sigma(Tr/ETo)$, where Tr is daily crop transpiration, and yield as $Y = B \times HI$, with the harvest index adjusted for the timing and severity of water stress (Raes et al., 2011). Water stress acts through canopy expansion, stomatal closure, early senescence and pollination failure (Steduto et al., 2009), and surface runoff is estimated with the curve number method (Raes et al., 2012). All simulations were fully rainfed. Crop parameters were taken from the default FAO crop files and adjusted to local conditions, with conservative parameters left at their default values (Raes et al., 2018). Soybean and maize were sown on 15 April and spring wheat on 22 March.

2.4 Scenarios and analysis

Five scenarios were simulated for each crop (Table 1); all other settings were identical. Four additional runs tested the assumptions: a 30% wind-speed reduction (all crops), a 30% curve number reduction (all crops), 100% mulch cover (maize), and maize on sandy loam.

Seasonal outputs were extracted for each crop, scenario and year: ETo, soil evaporation (E), relative transpiration (Tr/Trx), canopy expansion and stomatal closure stress, harvest index (HI), above-ground biomass, dry grain yield and water productivity for yield (WPet). Each 31-year series was summarised by its mean, minimum and maximum, and scenarios were compared with the control in absolute terms and as percentage changes. Drought years were analysed separately.

Table 1. Simulation scenarios.

Scenario	Measure	AquaCrop modification
S0 Control	Conventional rainfed management	Default settings
S1 CN reduction	Reduced surface runoff	CN 46 → 43 (sandy loam); 61 → 58 (silt loam)
S2 Mulch	Organic mulch cover	75% soil surface cover throughout the season
S3 Windbreak	Sheltering effect	Daily wind speed reduced by 50%

Scenario	Measure	AquaCrop modification
S4 Combined	All three measures	S1 + S2 + S3

RESULTS

3.1 Water balance and water stress

Under the control, rainfed soybean and spring wheat reached about two-thirds of their potential transpiration (Tr/Trx 66.7% and 69.0%) and maize reached 85.4% (Table 2). Curve number reduction left the water balance essentially unchanged. Mulching reduced mean soil evaporation by 26% (soybean), 28% (spring wheat) and 25% (maize), and the windbreak scenario reduced seasonal ETo by 12.6%, 12.9% and 12.6%, respectively. The combined scenario gave the highest Tr/Trx for every crop, with maize reaching 92.7%. For soybean, the share of ETo used as transpiration rose from 38.0% under the control to 47.8% under S4.

Water stress was highest for soybean and lowest for maize. Under the control, soybean canopy expansion stress peaked at 61% and stomatal closure stress at 41% in the driest years. The combined scenario reduced mean canopy expansion and stomatal stress by about 34% and 29% for spring wheat and by 56% and 47% for maize. Mean HI changed little; for soybean in 2000, however, HI rose from 34.6% under the control to 40.9% under S4.

3.2 Yield, biomass and water productivity

Control yields varied widely between years (Fig. 1), ranging from 0.84 to 4.32 t ha^{-1} for soybean, 1.62 to 6.58 t ha^{-1} for spring wheat and 4.74 to 12.68 t ha^{-1} for maize. The lowest yield of every crop occurred in 2000, and no crop failed completely in any year.

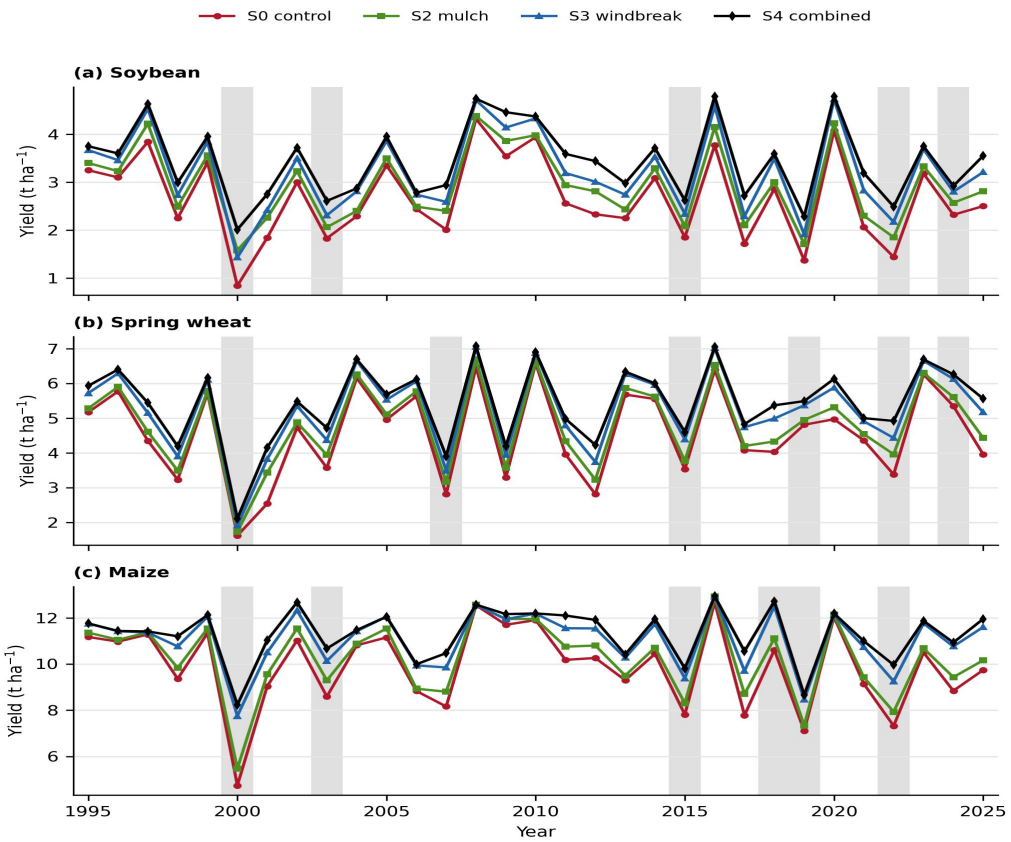

Figure 1. Annual dry grain yield of (a) soybean, (b) spring wheat and (c) maize under the control (S0), mulching (S2), windbreak (S3) and combined (S4) scenarios, 1995–2025. Shaded bands mark drought years (standardised growing-season water-deficit index ≤ −1).

On average, S1 did not change yield. The windbreak scenario gave the largest mean gain of the single measures for all crops, and the combined scenario gave the largest gain overall (Table 2, Fig. 2a). Biomass followed the same order, with S4 increases of 20.7% (soybean), 17.1% (spring wheat) and 13.0% (maize). In individual years the order sometimes differed: in 2000, soybean yield was higher under mulching (1.58 t ha^{-1}) than under the windbreak scenario (1.43 t ha^{-1}). In every year and for every crop, S4 yield was equal to or higher than the yield under any single measure.

Mean control WPet was 0.714 kg m^{-3} for soybean, 1.372 kg m^{-3} for spring wheat and 2.443 kg m^{-3} for maize. The combined scenario increased WPet by 38.2%, 24.9% and 25.2% (Fig. 2b) and raised the lowest values from 0.340 to 0.800 kg m^{-3} for soybean and from 0.870 to 1.030 kg m^{-3} for spring wheat.

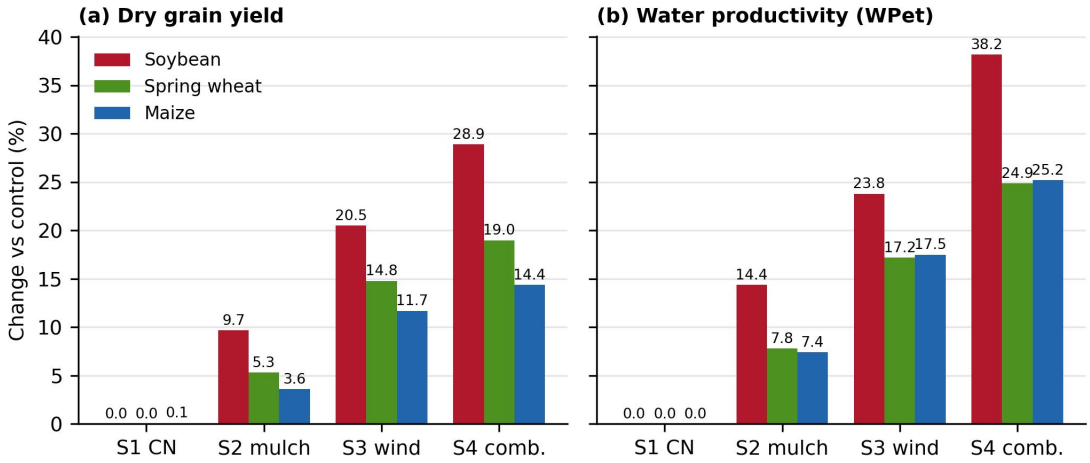

Figure 2. Change in 31-year mean (a) dry grain yield and (b) water productivity for yield (WPet) relative to the control, by scenario and crop.

Table 2. Mean seasonal outputs, 1995–2025. Yield Δ = change relative to S0.

Crop / scenario	ETo (mm)	E (mm)	Tr/Trx (%)	HI (%)	WPet (kg m^{-3})	Yield (t ha^{-1})	Yield Δ (%)
Soybean S0	635	123	66.7	37.2	0.714	2.665	—
S1	635	123	66.8	37.2	0.714	2.666	+0.0
S2	635	91	68.8	38.2	0.817	2.924	+9.7
S3	555	107	73.0	39.4	0.884	3.211	+20.5
S4	555	79	74.8	40.0	0.987	3.437	+28.9
Spring wheat S0	552	79	69.0	46.9	1.372	4.572	—
S1	552	79	69.0	46.9	1.372	4.572	+0.0
S2	552	57	71.2	47.3	1.479	4.814	+5.3
S3	481	66	75.9	47.8	1.607	5.248	+14.8
S4	481	47	77.6	48.0	1.714	5.438	+19.0
Maize S0	597	101	85.4	47.1	2.443	9.883	—
S1	597	101	85.4	47.1	2.444	9.891	+0.1
S2	597	76	86.9	47.2	2.624	10.242	+3.6
S3	522	89	91.5	47.7	2.871	11.040	+11.7
S4	522	66	92.7	47.8	3.058	11.302	+14.4

3.3 Drought years

In the reference drought year 2000, the combined scenario raised the yields of all three crops well above the control (Table 3). The soybean yield under S4 in 2000 (2.01 t ha^{-1}) was close to the 31-year control mean (2.67 t ha^{-1}), and no maize yield under S4 fell below 8.0 t ha^{-1} in any year. For every crop, the mean relative gain from combined measures in drought years exceeded the 31-year mean gain (Table 2).

Table 3. Drought years and yields under the control (S0) and combined scenario (S4).

Crop	Drought years (index ≤ −1; * severe)	Yield 2000, S0 (t ha^{-1})	Yield 2000, S4 (t ha^{-1})	Mean S4 yield gain in drought years (%)
Soybean	2000*, 2003, 2015, 2022, 2024	0.84	2.01	+52.8
Spring wheat	2000*, 2007, 2015, 2019, 2022, 2024	1.62	2.11	+26.9
Maize	2000*, 2003, 2015, 2018, 2019, 2022	4.74	8.23	+30.0

Note: the drought-year gains were recalculated from the year-by-year yields of the thesis appendix using the index-defined drought years; verify them against the model output before submission.

3.4 Sensitivity analyses

With a 30% instead of a 50% wind-speed reduction, mean yield gains fell to 11.2% (soybean), 8.1% (spring wheat) and 6.6% (maize), and the ranking of crops was unchanged. Increasing the curve number reduction to 30% changed mean yields by less than 0.1% for soybean and spring wheat and by 0.3% for maize; mean simulated seasonal runoff was only 0.2–3.1 mm, and most seasons had no runoff at all. Raising maize mulch cover from 75% to 100% increased mean yield from 10.24 to 10.37 t ha^{-1}, a further gain of 1.2%. When maize was simulated on sandy loam, its yield declined by roughly 31% and its water stress roughly doubled.

DISCUSSION

The results partly support H1: mulching and wind-speed reduction increased yield and water productivity for all crops, but curve number reduction did not. H2 was supported, since the combined scenario gave the highest mean yields and water productivity for every crop. H3 was also supported, because the relative gains in drought years exceeded the 31-year mean gains.

Wind-speed reduction was the most effective single measure, acting by lowering atmospheric demand and thus ETo by about 13%. This agrees with field evidence: Kort (1988) reported weighted-mean yield increases of about 12% for maize and 8% for spring wheat, and the simulated maize gain (+11.7%) closely matches the first figure, while the spring wheat gain (+14.8%) exceeds the second. The simulated ETo reduction is consistent with measurements near an eastern Austrian hedgerow (Gollobich et al., 2026) and in a sheltered vineyard (Veste et al., 2020), and the benefit was not an artefact of the 50% setting, since a 30% reduction also produced clear gains. The model represents shelter in a simplified way. Sheltered plants tend to grow taller with larger leaf areas, which increases water demand, and where soil water-holding capacity is limited sheltered crops can become more stressed than exposed ones (Brandle et al., 2004). Real windbreaks also create a spatial gradient, with a protected zone typically extending 10–30 times the windbreak height (Brandle et al., 2004) and competition reducing yields over roughly 0.5–2 times the height close to the trees (Kort, 1988).

Mulching increased yields by 3.6–9.7%, less than in the meta-analysis of Qin et al. (2015). The simulated organic mulch acts more like straw than plastic film, which gave the larger benefits in that analysis, and AquaCrop represents mulch only as a suppression of soil evaporation, not as soil warming, faster early growth or weed suppression. The simulated benefit was smallest for maize and saturated below full cover, since raising mulch cover to 100% added only 1.2% yield.

Curve number reduction had a negligible effect even when increased six-fold, because almost no surface runoff was available to recover. This reflects the flat topography and freely draining soils of the site, and the result should not be transferred to sloping land or soils with high runoff potential.

The combined scenario gave gains approximately equal to the sum of the mulching and wind-speed effects, which suggests that the two effective measures act through largely independent pathways: mulch reduces soil evaporation, whereas shelter reduces atmospheric demand. Seasonal outputs cannot, however, exclude minor interactions. The largest relative benefits occurred in drought years, which agrees with the larger shelter responses reported for drier regions and years (Kort, 1988).

Soybean gained most in relative terms and maize least. Two explanations should be considered. First, soybean had the lowest control yield, so a given absolute gain produces a larger percentage. Second, crop and soil effects are confounded, because maize was simulated on silt loam and the C3 crops on sandy loam; the supplementary maize run on sandy loam supports this, since yield fell by roughly 31%. The higher water productivity of maize is nevertheless consistent with measured values, which are higher for maize than for C3 cereals (Zwart & Bastiaanssen, 2004). Simulated WPet fell within measured ranges for irrigated crops: 2.443 kg m^{-3} for maize lies at the upper end of the reported 1.1–2.7 kg m^{-3}, and 1.372 kg m^{-3} for spring wheat within the 0.6–1.7 kg m^{-3} range (Zwart & Bastiaanssen, 2004). For soybean, Zheng et al. (2026) reported a global mean WPet of 0.64 kg m^{-3}, a European mean of 0.56 kg m^{-3} and a theoretical European potential of 0.96 kg m^{-3}; the simulated control value (0.714 kg m^{-3}) exceeds the European mean and the combined-scenario value (0.987 kg m^{-3}) slightly exceeds the theoretical potential.

The main limitation is that simulated yields were not validated against measured yields at the site, so absolute values should be read as internally consistent scenario comparisons rather than yield predictions; AquaCrop requires separate parameterisation and validation for each combination of climate, soil and variety (Zhang et al., 2025). The measures were applied uniformly in space and time, below-ground competition from windbreak trees was not represented (Cleugh, 1998), and AquaCrop does not reproduce damage from extreme weather such as wind-induced lodging (Zhou et al., 2024). Phenology was specified in calendar days, each crop was simulated on one soil only, and the analysis covered one site and was purely biophysical, without establishment or maintenance costs.

CONCLUSIONS

Reducing wind speed was the most effective single measure for soybean, spring wheat and maize on the flat Marchfeld plain, and it remained effective at a conservative 30% reduction. Combining mulching with shelter gave the largest and most consistent gains, through two largely additive pathways. Reducing runoff had no effect on this flat, freely draining site, and this result should not be generalised to sloping land.

The main practical value of the measures lies in raising the lowest yields in dry years rather than only raising average yields, so shelterbelts combined with residue cover are a credible adaptation option as growing-season water deficits intensify. Future work should validate the simulated responses against measured yields, simulate each crop on both soils, represent the spatial gradient of shelter, and add an economic assessment.

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