Modeliranje biljne proizvodnje u konsocijacijskim sustavima oraha i ratarskih kultura

Žalac, Helena

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Modeliranje biljne proizvodnje u konsocijacijskim sustavima oraha i ratarskih kultura
Helena Žalac, mag. ing. agr.

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Konsocijacijski sustavi često su produktivniji po jedinici površine (LER>1) i usvojene vode (WER>1) nego pojedinačni sustavi. Korištenjem simulacijskih modela Yield-SAFE i Farm-SAFE analizirane su mogućnosti usijavanja ratarskih kultura u voćnjak oraha u budućim klimatskim uvjetima naše regije, s aspekta produktivnosti i isplativosti. Nadalje, analizirana je produktivnost i učinkovitost usvajanja vode u sustavima orah-heljda, orah-ječam i orah-kukuruz, a tijekom vegetacije kukuruza detaljnije su analizirani mikroklima i rast, komponente prinosa te korištenje vode i hranivih tvari kukuruza. Modelima je procijenjeno da bi, unatoč smanjenju prinosa usjeva, konsocijacijski sustavi bili produktivniji od odvojenog uzgoja oraha i usjeva, čak i nakon 20 godina. Simulirani scenarij s usijavanjem ratarskih kultura tijekom šest godina i zatim održavanja samo voćnjaka pokazao se najisplativijim tijekom simuliranog razdoblja od 20 godina. Značajan utjecaj na mikroklimu zabilježen je u starijem voćnjaku, što je rezultat većih stabala oraha i užih razmaka sadnje. LER vrijednosti bile su 1,05, 1,32 i 1,53, a WER 1,12, 1,31, i 1,83 za sustave s heljdom, kukuruzom i ječmom, redom. U konsocijaciji oraha i kukuruza uočen je negativan utjecaj stabala oraha na klijavost kukuruza, što je rezultiralo značajno manjim prinosom po ukupnoj površini u odnosu na prinos kukuruza na kontrolnoj parceli. Međutim, kukuruz u konsocijaciji ostvario je veći žetveni indeks i značajno veću masu 1000 zrna. Nisu pronađene značajne razlike između promatranih sustava kukuruza u produktivnosti po jedinici raspoloživih hraniva u tlu, niti u učinkovitosti mobilizacije dostupnih hraniva u zrno. Ipak, kukuruz u konsocijaciji dao je veći prinos zrna po jedinici apsorbiranog dušika i kalija. Ovo istraživanje pokazalo je da konsocijacija ratarskih kultura i oraha može biti održiva mjera intenziviranja poljoprivredne proizvodnje ili isplativ način prelaska s ratarske na voćarsku proizvodnju.

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Modeling of plant production in intercropped systems of walnut and arable crops
Helena Žalac, M. Eng. Sc. Agr

Thesis performed at Faculty of Agrobiotechnical Sciences Osijek, University of Josip Juraj Strossmayer in Osijek
Supervisor: Assoc. Prof. Vladimir Ivezić, PhD

Intercropped systems are often more productive per unit area (LER>1) and unit of water uptake (WER>1) than sole systems. Using the Yield-SAFE and Farm-SAFE simulation models, the possibilities of intercropping in walnut orchards in the future climatic conditions of our region were analyzed from the aspect of productivity and profitability. Furthermore, the productivity and water use efficiency in walnut-buckwheat, walnut-barley and walnut-maize systems were assessed, and during the maize growing season, the microclimate and growth, yield components and the use of water and nutrients of maize were analyzed in detail. The models estimated that, despite the reduction in crop yields, intercropped systems would be more productive than monoculture systems, even after 20 years. The simulated scenario with intercropping for six years and then maintaining a sole orchard proved to be the most profitable during the simulated period of 20 years. A significant impact on the microclimate was recorded in the older orchard, which is the result of larger walnut trees and narrower planting distances. LER values were 1.05, 1.32, and 1.53, and WER 1.12, 1.31, and 1.83 for buckwheat, maize, and barley systems, respectively. In the walnut-maize system, a negative effect of walnut trees on the germination of maize was observed, which resulted in a significantly lower yield per total area compared to the yield of monoculture maize. However, intercropped maize achieved a higher harvest index and significantly higher 1000 kernel weight. No significant differences were found between observed maize systems in productivity per unit of available nutrients in the soil, nor in the efficiency of mobilization of available nutrients into grain. Nevertheless, intercropped maize produced a higher grain yield per unit of absorbed nitrogen and potassium. This research showed that intercropping arable crops in walnut orchard can be a sustainable measure of agricultural production intensification or a cost-effective way of switching from arable to fruit production.

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KAZALO

1. UVOD

Konvencionalna poljoprivredna proizvodnja, temeljena na velikim inputima energije i agrokemijskih sredstava, predstavlja jedan od najvećih zagađivača okoliša te ima direktni utjecaj na klimatske promjene. S druge strane, tijekom posljednih desetljeća postalo je očigledno i da će klimatske promjene biti značajna prijetnja poljoprivrednoj proizvodnji, osobito u aridnim i semi-aridnim područjima sklonim sušama. Trend porasta temperature zbog klimatskih promjena već je dobro ustanovljen i mnoge buduće klimatske projekcije pokazuju da je nastavak ovog trenda neizbježan (Raftery i sur. 2017). Općenito, mnoge će se regije tijekom ljeta suočiti s toplijim i sušnijim uvjetima, što ukazuje na visok rizik za proizvodnju i sigurnost hrane. Iz navedenih razloga, znanstvenici i poljoprivrednici konstantno su u potrazi za održivim alternativama konvencionalnoj poljoprivredi koje mogu očuvati prirodne proizvodne kapacitete zemljišta uz minimalni utrošak energije i resursa te optimizirati iskoristivost vode i hranivih tvari.

Održivost poljoprivredne proizvodnje pospješuju mješoviti uzgoji više poljoprivrednih vrsta, bilo da se radi o konsocijaciji poljoprivrednih kultura ili nekom drugom obliku agrošumarstva (Barea i Jeffries, 1995). Agrošumarstvo podrazumijeva združeni uzgoj drvenastih vrsta i poljoprivrednih usjeva – silvo-obradivi tip (konsocijacija) te drvenastih vrsta i životinja/stoke – silvopastoralni tip agrošumarstva, kao i neke druge oblike i kombinacije objedinjenog uzgoja više biljnih i životinjskih vrsta. Ovakvi su sustavi bili tradicionalna praksa u predindustrijskoj eri, ali su zbog povećane potražnje za hranom, šume i agrošumarske površine polako nestajale kako bi se svaki komad obradivog tla iskoristio za intenzivnu poljoprivrednu proizvodnju. U posljednjih nekoliko desetljeća, uz rastuću svijest o očuvanju okoliša, agrošumarstvo ponovo dobiva na popularnosti i ističe se kao jedna od najboljih održivih alternativa konvencionalnoj poljoprivredi. U Europi je agrošumarstvo već postalo značajan način upotrebe zemljišta, s ukupno 15,4 milijuna hektara, a najveća područja nalaze se u južnoj Europi (Španjolska, Portugal). Većina površina pod silvopastoralnim sustavima, oko 222 000 ha agrošumarstva, obuhvaća silvo-obradive sustave s drvećem visoke vrijednosti kao što su voćke (masline, lupinaste voćke i ostale voćke) (Herder i sur., 2017; Pantera i sur., 2018).

Dodatak drveća agroekosustavima ima veliki potencijal za ublažavanje klimatskih promjena i očuvanje okoliša povećanjem fiksacije atmosferskog dušika i ugljičnog dioksida te povećanjem sekvestracije ugljika u drvnu masu i tlo (Cardinael i sur., 2017; Cong i sur., 2015), povećanjem bioraznolikosti (Torralba i sur., 2016), smanjenjem ispiranja hranivih tvari i pesticida čime se čuvaju podzemne vode (Pardon i sur., 2017) i sprječavanjem erozije tla (Blanco-Sepúlveda i Carrillo, 2015). Također, agrošumarski sustavi omogućavaju i bolju prilagodbu sustava proizvodnje hrane promjenjivim klimatskim uvjetima (Hernández-Morcillo i sur. 2018). Prije svega, drveće mijenja mikroklimu obradivog područja, prvenstveno utječući na intenzitet sunčevog zračenja, smanjujući temperaturu zraka i jačinu vjetra, čime se povećava relativna vlažnost zraka. Ove promjene dovode do smanjenja evapotranspiracije i poboljšanja korištenja vode u ovakvim sustavima, te u konačnici do stabilnijih mikroklimatskih uvjeta za usjeve koji se uzgajaju ispod drveća.

Ekološke prednosti sadnje drveća na obradivim površinama potaknule su Europsku uniju da pruži financijsku potporu novim agrošumarskim sustavima. Između 2007. i 2013. godine, EU programi ruralnog razvoja uključivali su Uredbu 1698/2005 (The Council of the European Union, 2005) koja je promovirala uspostavljanje novih agrošumarskih sustava na obradivim zemljištima. Međutim, iz perspektive poljoprivrednih proizvođača, za uspostavu ovakvih sustava, presudan je odgovor na pitanje koliko produktivni i isplativi konsocijacijski sustavi mogu biti, odnosno, kako bi ovakav kombinirani uzgoj utjecao na prinose poljoprivrednih kultura? S obzirom da produktivnost, održivost i isplativost konsocijacijskih sustava ovise o mnogo čimbenika, teško je dobiti relevantne zaključke o istima bez dugotrajnih i opsežnih istraživanja, kojih u Republici Hrvatskoj za sada nema. Jedan od načina za utvrđivanje uspješnosti ovakvih sustava jest korištenje simulacijskih modela. Modeli nam pomažu u razumijevanju odnosa između tla, biljaka i ostalih komponenti sustava, te služe kao koristan alat u odlučivanju o najboljim opcijama upravljanja za postizanje optimalne produktivnosti. Od 2001. Europska unija financirala je agrošumarske projekte SAFE i AGFORWARD unutar kojih su razvijeni kompjuterski modeli Yield-SAFE - biofizički model (Van der Werf i sur., 2007) i Farm-SAFE - bioekonomski model (Graves i sur., 2011) s ciljem informiranja europskih poljoprivrednika, ali i zakonodavnih tijela u području poljoprivrede o potencijalima agrošumarskih, odnosno konsocijacijskih sustava.

Prethodna istraživanja konsocijacijskih sustava s drvenastim vrstama na razini Europe temeljila su se uglavnom na uzgoju drveća za proizvodnju drvne mase (Graves i sur., 2010; Palma i sur., 2007; Van der Werf i sur., 2007), te je vrlo malo istraživanja o uspješnosti konsocijacijskih sustava s drvenastim vrstama uzgajanih radi voća. Potaknut državnim subvencijama, u Republici Hrvatskoj posljednjih godina raste interes za voćarstvom, osobito za uzgojem oraha. Uočen je stalni porast ukupnih površina pod voćnjacima oraha od 2014. godine, a prema posljednjim podacima, pokriva drugo najveće područje u proizvodnji voća, nakon nasada maslina (Statistički ljetopis, 2018).

Slijedom svega navedenog, ciljevi ove doktorske disertacije bili su: simulacijskim modelom ispitati potencijalnu produktivnost i isplativost usijavanja poljoprivrednih kultura u voćnjake oraha različite gustoće sadnje; ispitati stvarnu produktivnost i učinkovitost usvajanja vode konsocijacijskih sustava oraha s heljdom, ječmom i kukuruzom; analizirati mikroklimatske parametre i parametre rasta tijekom vegetacije kukuruza u sustavu orah-kukuruz, te utvrditi potencijalne prednosti pri usvajanju glavnih makrohraniva.

2. PREGLED LITERATURE

Klimatske promjene podrazumijevaju pojavu sve češćih ekstremnih uvjeta, a poseban rizik za poljoprivrednu proizvodnju donose sve topliji i sušniji uvjeti tijekom ljetnih mjeseci. Procjena klime u Hrvatskoj koju su proveli Perčec Tadić i sur. (2014), pokazuje da se prevladavajući deficit oborina javlja tijekom tople sezone. Što se tiče Panonske regije, gdje je većina obradivih površina, manjak oborine se javlja na mjesečnoj razini. Najizraženiji je u istočnom dijelu regije od travnja do rujna. Autori su ovo područje svrstali u srednje osjetljivo na sušu, a najosjetljivije su oranice koje se uglavnom ne navodnjavaju.

Prirodni sustavi, kao što su šume, mogu vrlo učinkovito koristiti dostupne resurse bez potrebe za agrotehničkim mjerama, a njihova biološka raznolikost omogućuje dinamičku prilagodbu promjenama u okolišu i klimatskim uvjetima. Wilson i Lovell (2016) naglašavaju da bi poljoprivredni sustavi bili stabilniji i održiviji kada bi imali više karakteristika takvih prirodnih sustava, a upravo to je ono čemu teži agrošumarska praksa.

Važnost silvoarabilnih agrošumarskih sustava uvelike se ogleda u kontekstu klimatskih promjena. Naime, ovakvi sustavi imaju znatnu sposobnost fiksacije atmosferskog dušika i ugljičnog dioksida, povećane sekvestracije ugljika u drvnu masu te u tlo (Cong i sur., 2015; Cardinael i sur., 2017) čime se smanjuje negativan doprinos poljoprivredne proizvodnje klimatskim promjenama. Osim toga, prednosti inkorporacije drveća na obradivim površinama djeluju i u drugom smjeru – u ovakvim sustavima dolazi do stvaranja svojevrsne mikroklime koja omogućuje bolje iskorištenje vode te obećava bolju prilagodbu poljoprivredne proizvodnje sve izraženijim klimatskim ekstremima (Gosme i sur., 2016; Quinkenstein i sur., 2009). Naime, drveće svojom krošnjom smanjuje jačinu vjetra, a zasjenom koju stvara smanjuje temperaturu zraka i tla te povećava vlažnost. Time se smanjuje prije svega evaporacija, tj. gubitak vode iz tla, ali i transpiracija biljaka, što u konačnici osigurava stabilnije uvjete i učinkovitije korištenje dostupne vode za proizvodnju biomase i prinosa, nego što je to slučaj u tradicionalnim ratarskim ili voćarskim praksama (Bai i sur., 2016; Gosme i sur., 2016; Panozzo i sur., 2022).

Ipak, poljoprivredni proizvođači su skeptični oko uspostavljanja agrošumarskih, odnosno konsocijacijskih sustava ponajviše zbog zabrinutosti o produktivnosti takvih sustava s obzirom na smanjenu površinu pod poljoprivrednim usjevima i kompeticiju za resurse za drvećem (Seserman i sur., 2019), kao i nesigurnosti o financijskoj isplativosti (Graves i sur., 2017). Prije svega, prinose usjeva određuju svojstva klime i tla. Međutim, vrste drveća, starost, gustoća i upravljanje značajno utječu na količinu sjene i kompeticiju za podzemne resurse, tako da različite kombinacije vrsta u tim sustavima daju vrlo različite rezultate (Rao i sur., 2007). Iako je smanjenje prinosa usjeva u sustavima s drvećem očekivano i zabilježeno, istraživanja su pokazala da se pravilnim dizajnom sustava i odabirom vrsta kompeticije mogu smanjiti na razinu na kojoj usjev može ostvariti iste prinose kao usjev u monokulturi (Reynolds i sur., 2007), ako ne i više (Burgess i sur., 2005; Seserman i sur., 2019). Također, brojna eksperimentalna istraživanja (Bai i sur., 2016; Dupraz i sur., 2011; Rivest i sur., 2010), kao i simulacijski modeli konsocijacijskih sustava (Graves i sur., 2007; Sereke i sur., 2015) pokazali su da ovakvi sustavi, bez obzira na smanjene relativne prinose, mogu ostvariti značajno veću produktivnost nego pojedinačni uzgoji istih kultura. Ukupna produktivnost konsocijacijskih sustava najčešće se računa indeksom *Land Equivalent Ratio* (LER). LER se može definirati kao omjer površine pod konsocijacijskim sustavom i površine pod pojedinačnom proizvodnjom potreban za postizanje jednakih prinosa na istoj razini upravljanja (Ong i Kho, 2015). Računa se kao zbroj omjera prinosa stabala u konsocijacijskom sustavu i prinosa zasebno uzgajanih stabla i omjera prinosa usjeva u konsocijacijskom sustavu i prinosa usjeva s parcele bez drveća (Mead i Willey, 1980). Drugim riječima, to je zbroj relativnog prinosa drvenaste vrste i relativnog prinosa usjeva. Kada je LER=1, nema agronomske prednosti konsocijacijskih sustava u odnosu na pojedinačni uzgoj promatranih kultura, ali kada je LER>1, produktivnost po jedinici površine veća je nego u odvojenim sustavima. To znači da bi za proizvodnju jednakih prinosa kao u konsocijacijskom, pojedinačni sustavi zahtijevali veću površinu. Produktivnost agrošumarskih sustava, prije svega prinosi poljoprivrednih kultura, značajno ovise o kombinaciji vrsta. Reynolds i sur. (2007) navode da drveće zasjenom smanjuje sunčevu radijaciju za usjev C3 poljoprivrednih kultura i do 50%, no te biljke i dalje mogu ostvariti fotosintetski potencijal, bez gubitaka prinosa u odnosu na prinose te kulture uzgajane zasebno. Naprotiv, za C4 biljke i najmanja zasjena može rezultirati značajnim smanjenjem fotosinteze i u konačnici, prinosa. Slično, rezultati istraživanja Yung Ying i Zhao Hua (1997) pokazali su porast prinosa đumbira u konsocijaciji s paulovnijom od čak 34% u odnosu na prinos đumbira uzgajanog bez paulovnije. Ovakve rezultate objašnjavaju činjenicom da je đumbir C3 tolerantna biljka na sjenu, ali i time da paulovnija ima rijetku krošnju s relativno kasnim listanjem te ranim opadanjem lišća, zbog čega je zasjenjivanje kratkotrajno i nema značajnog utjecaja na rast đumbira. Pardon i sur. (2018) u svom trogodišnjem istraživanju konsocijacije topole i poljoprivrednih usjeva utvrdili su da je topola utjecala na smanjenje prinosa kukuruza, krumpira, ozimog ječma i ozime pšenice. Smanjenje prinosa poljoprivrednih kultura ponajviše je ovisilo o starosti nasada topole i vrsti usjeva pa je tako najveće smanjenje prinosa zabilježeno u konsocijaciji sa starijim nasadima topole (15-48 godina) i to za kukuruz i krumpir, koje su ljetne kulture. Burgess i sur. (2005) u konsocijacijskim pokusima s topolom i usjevima ječma, graha, pšenice, graška i gorušice utvrdili su da su prinosi usjeva u ovim sustavima u prvoj godini, kada je nasad topole podignut, bili veći od prinosa na parcelama na kojima su poljoprivredne kulture uzgajane zasebno. Ipak, do treće godine prinosi usjeva u konsocijaciji bili su u prosjeku manji za 4% nego na kontrolnoj parceli bez topole, a između četvrte i šeste za prosječno 10%. Kao glavni ograničavajući čimbenik smanjenja prinosa usjeva u konsocijaciji navode zasjenjivanje, što potkrjepljuju i zapažanjima da je topola imala veći utjecaj na prinose jarih kultura nego ozimih žitarica. Pardon i sur. (2019) također su potvrdili kako su ozime kulture bolji odabir za konsocijacijske sustave od jarih zbog kraćeg preklapanja vegetacijskih sezona. U istraživanju prinosa usjeva ozime pšenice, ozimog ječma, ozimog tritikalea, kukuruza i šećerne repe u konsocijaciji s orahom, zabilježili su smanjenje prinosa ovih kultura na manjim udaljenostima od stabala oraha, s tim da smanjenje prinosa ozimih žitarica nije bilo toliko izraženo kao kod kukuruza i šećerne repe. Osim negativnog utjecaja topole na prinose usjeva u konsocijaciji, Burgess i sur. (2005) zabilježili su i negativan utjecaj usjeva na rast topole. Nakon sedam godina, prosječna visina stabala topole bila je za 10% manja, a prosječni promjer stabla za 21% manji u odnosu na kontrolni nasad topole bez poljoprivrednih usjeva. Kao glavni razlog ovih rezultata navode kompeticiju drveća sa usjevima za vodu i/ili hranive tvari. Snažnu ulogu vode podupire i opažanje da je utjecaj usjeva na rast topole bio najizraženiji tijekom suhog ljeta 1995. godine.

Istražujući sustave crnog oraha i kukuruza te crvenog hrasta i kukuruza, Jose i sur. (2000) otkrili su da je kompeticija za vodu s korijenjem drveća, a ne zasjena, bila glavni ograničavajući čimbenik za produktivnost kukuruza. Naime, utvrdili su veće usvajanje vode od strane kukuruza na parceli gdje su postavljene barijere između korijenja drveća i kukuruza, nego na parceli gdje se korijenje moglo slobodno širiti. Mnogi drugi autori također tvrde da je kompeticija, odnosno komplementarnost u usvajanju vode u konsocijacijskim sustavima ključna za produktivnost sustava (Miller i Pallardy, 2001; Wanvestraut i sur., 2004; Gao i sur., 2013). Ovisno o hidrološkim karakteristikama tla, vrstama drveća i usjeva i morfologiji njihovog korijena, sezonskim zahtjevima i razini konkurentnosti, podzemne interakcije stabla i usjeva mogu značajno varirati. Unatoč svemu tome, neka istraživanja upućuju na to da pri nedostatnoj količini vode u tlu drveće može 'odabrati' usvajati vodu iz dubljih slojeva tla, i time smanjiti kompeticiju s usjevima u plićim slojevima te omogućiti komplementarno usvajane vode u sustavu (Bayala i Prieto, 2019). Takva komplementarnost uočena je između stabala topole i kukuruza te stabala jabuke i kukuruza, gdje je kukuruz crpio vodu iz tla na dubinama od 0-60 cm, a primarni izvori vode za drveće bili su ispod 60 cm dubine tla (Liu i sur., 2018; Liu i sur., 2020). Slično, Bai i sur. (2016) otkrili su da su u konsocijacijskim sustavima s marelicom usjevi crpili vodu iz gornjih slojeva tla, u kojima nije bilo aktivnosti korijena marelice, što je rezultiralo poboljšanim korištenjem vode u odnosu na parcele sa zasebnim uzgojem istraživanih kultura. Autori su učinkovitost usvajanja vode ovih sustava prikazali kao zbroj ukupnih relativnih prinosa po jedinici usvojene vode u konsocijaciji, u usporedbi sa sustavima pojedinačnog uzgoja. Njihovi rezultati pokazali su da bi za prinose kikirikija, prosa i batata (ostvarene u konsocijaciji) uzgajanim na zasebnim parcelama trebalo 39%, 51% i 34% više vode. Ove vrijednosti proizlaze iz izračuna indeksa *Water Equivalent Ratio* (WER) koji se definira kao relativni ukupni prinos po jedinici vode u konsocijacijskom sustavu u usporedbi s pojedinačnim sustavima (WER vrijednosti: 1.39, 1.51, 1.34). WER indeks tumači se analogno LER indeksu, što znači da vrijednosti WER>1 ukazuju na to da za proizvodnju jednakih prinosa potrebno manje vode u konsocijacijskom nego u pojedinačnim sustavima.

Jedan od najvažnijih potencijala konsocijacijskih sustava je smanjenje ovisnosti o kemijskim inputima omogućavanjem bolje iskoristivosti hraniva u tlu (Zhu i sur., 2019) i ujedino smanjenja ispiranja hraniva čime se čuvaju podzemne vode (Pardon i sur., 2017). Naime, drveće u ovim sustavima može pospješiti usvajanje hraniva na nekoliko načina: smanjenjem gubitaka putem tzv. 'sigurnosne mreže' (eng. safety net) odnosno intercepcijom ispranih hraniva u dubljim slojevima tla koji su nedostupni korijenju jednogodišnjih usjeva; 'podizanjem' tih hraniva u pliće slojeve; promjenama u kemijskim procesima u rizosferi raznim korijenskim aktivnostima kojima se povećava topivost hraniva; dijeljenjem zajedničke mikorizne mreže; te dodatkom dušika iz atmosfere u slučaju N-fiksirajućeg drveća (Isaac i Borden, 2019). Lawson i sur. (2020) navode kako agrošumarski sustavi putem raznih procesa u tlu imaju velik potencijal za poboljšanje dostupnosti dušika i drvenastim i zeljastim vrstama u sustavu, što je i zabilježeno povećanjem koncentracije dušika i sadržaja proteina u zrnu raznih ratarskih usjeva. Pardon i sur. (2019) pokazali su da je smanjen prinos zrna ozimih žitarica u konsocijaciji djelomično nadoknađen povećanom koncentracijom proteina u zrnu biljaka koji su bili bliže stablima oraha. Slične rezultate ostvarili su i Artru i sur. (2016); primjerna umjetne sjene bila je povezana s manjim zrnom pšenice nego na nezasjenjenoj parceli, ali je utvrđena veća koncentracija proteina u zrnu tih biljaka. Rezultati istraživanja Haggar i sur. (1993) na pokusima s kukuruzom u konsocijacijskim sustavima pokazali su da je kukuruz ostvario veću biomasu i imao veći sadržaj dušika u ovim sustavima, u odnosu na kukuruz s kontrolne parcele bez drveća. Harawa i sur. (2006) ostvarili su slične rezultate – koncentracija dušika u listu kukuruza, ukupno usvajanje dušika i prinosi kukuruza bili su značajno veći u konsocijacijskom sustavu. Sharma i sur. (2012) u istraživanju konsocijacijskog sustava pšenice i topole utvrdili su da je akumulacija suhe tvari pšenice, kao i usvajanje N, P i K bilo značajno niže u blizini 0 – 3 m od stabala topole, u odnosu na kontrolu. Međutim, na udaljenosti 3 – 9 m od stabala, vrijednosti promatranih parametara bile su veće nego na kontroli, što ukazuje na pozitivan učinak drveća, ali i na važnost pravilnog dizajna ovih sustava. Učinkovitost usvajanja pojedinih hraniva s obzirom na producirani prinos ili biomasu može se računati pomoću raznih indeksa i odnosa između koncentracija hraniva u biljnom tkivu i u tlu (Congreves i sur., 2021).

Simulacijskim modelima moguće je predvidjeti ograničenja i učinke raznih uvjeta poljoprivrednih sustava, a u konačnici i produktivnost i isplativost istih, što je od osobite važnosti za podizanje trajnih nasada i kombinirani uzgoj različitih vrsta. Biofizički Yield-SAFE model (van der Werf i sur., 2007) i bioekonomski Farm-SAFE model (Graves i sur., 2011) razvijeni su za informiranje Europskih poljoprivrednika i nadležnih političkih tijela o potencijalu konsocijacijskih sustava kao dio EU projekta SAFE između 2001. i 2005. Oba ova modela su dodatno nadograđena tijekom projekta AGFORWARD pod pokroviteljstvom EU između 2014. i 2017. (Burgess i Rosati, 2018). Razvoj modela uključio je i stvaranje baze klimatskih podataka pod nazivom CliPick (Palma, 2017), pomoću koje je moguće simulirati procese u konsocijacijskim sustavima pod utjecajem klimatskih promjena. Sereke i sur. (2015) u istraživanju produktivnosti i financijske isplativosti agrošumarskih sustava u Švicarskoj simulirali su različite financijske scenarije agrošumarskih praksi, te su utvrdili da je 68% scenarija bilo isplativije od tradicionalnih sustava pojedinačnih uzgoja, a posebice scenariji koji su bili povezani s inovativnim marketingom voća ili primanjem prihoda za usluge ekosustava. Plaćanja za usluge ekosustava uvelike utječu na isplativost agrošumarskih sustava, zbog čega rezultati ovih istraživanja značajno variraju s obzirom na politiku pojedinih država. Tako su Kay i sur.

(2019) u svom istraživanju na razini Europe utvrdili da su mediteranski agrošumarski sustavi ostvarili veću financijsku vrijednost nego tradicionalni poljoprivredni sustavi, dok je u atlantskim i kontinentalnim regijama utvrđeno suprotno. Međutim, kada su uključili ekonomske vrijednosti usluga ekosustava, relativna isplativost tih agrošumarskih sustava se povećala. Slične rezultate ostvarili su i García de Jalón i sur. (2018) u svom simulacijskom modelu: Tradicionalni poljoprivredni sustav ostvario je najveću profitabilnost u odnosu na agrošumarski i šumarski sustav. Međutim, kada su u izračun uključili usluge ekosustava (kao što su povećana sekvestracija ugljika, smanjeno onečišćenje voda i povećana bioraznolikost), najprofitabilniji je bio agrošumarski sustav.

Prethodna istraživanja o održivosti konsocijacijskih sustava s drvećem u Europi uglavnom se temelje na korištenju drveća za proizvodnju drva (Palma i sur., 2007; van der Werf i sur. 2007.; Graves i sur. 2007.; Graves i sur., 2010.). Nasuprot tome, tek nekoliko istraživanja bavilo se biofizičkim i financijskim aspektima sustava koji uključuju drveće voćaka. Stabla oraha (vrste roda *Juglans*) daju plod visoke nutritivne vrijednosti, bogat bjelančevinama, mineralima i vitaminima, a ulje oraha smatra se izrazito zdravim za razne primjene (Ozkan i Koyuncu, 2005). Obični orah (*Juglans regia* L.), koji se naziva i engleski ili perzijski orah, uzgaja se u raznim klimatskim i zemljišnim uvjetima, ali su prinosi najveći u toplim i umjerenim krajevima. Ahmad i sur. (2018) tvrde da optimalni uvjeti uzgoja oraha podrazumijevaju oko 760–800 mm dobro raspoređenih godišnjih oborina, duboka, dobro propusna ilovasta tla s pH 5,5–6,5 i bogata humusom. Preporučena gustoća stabala u voćnjaku ovisi o klimi, uvjetima tla i kultivaru (Ahmad i sur., 2018). U Hrvatskoj se orah obično sadi na razmak od 10 * 10 m (100 stabala ha^{-1}) do 5 * 5 (400 stabala ha^{-1}) za intenzivne nasade s manjim, lateralnim sortama. Iako cijepljeni orasi mogu roditi svoje prve plodove već u 3. ili 4. godini, značajan prinos ne ostvaruju prije 8. godine. Ne postoji referentna publikacija o prinosima oraha u Hrvatskoj, ali prema Savjetodavnoj službi Ministarstva poljoprivrede, dobro održavani nasad u punoj zrelosti može ostvariti prinos od 3,5–4 tone po hektaru oraha u ljusci, mada i to zavisi od kultivara i odgovarajuće rezidbe (Orah - značajna voćna vrsta 2007). Pogodnost oraha za konsocijacijske sustave leži u njegovim morfološkim i fenološkim značajkama: nepravilna, poluotvorena krošnja propušta poprilično veliki udio sunčeve svjetlosti do kultura koje rastu ispod nje, a orahovo kasno listanje odgađa zasjenjivanje, što je osnova vremenske komplementarnosti u sustavima s ozimim, ali i konkurentski čimbenik u sustavima s jarim kulturama. Nadalje, stablo oraha razvija dubok i ne previše razgranat glavni korijen, koji ima potencijal djelomično eliminirati podzemnu kompeticiju s usjevima (Tengas, 1994; Gillespie i sur., 2000). Međutim, ova svojstva mogu varirati ovisno o različitim okolišnim uvjetima, tipovima tla, primjenjivanoj agrotehnici itd. Još jedan važan aspekt koji treba uzeti u obzir pri uspostavljanju konsocijacijskih sustava sa stablima oraha je potencijalni alelopatski učinak. Naime, stabla oraha proizvode različite organske tvari koje mogu djelovati inhibitorno na biljke koje rastu u blizini, a najistaknutiji je juglon (5-hidroksi-1,4-naftokinon). Juglon se nalazi u svim organima drveća, ali je posebno koncentriran u lišću, ljuskama plodova i korijenju (Kocacë Aliskan i Terzi, 2001).

3. CILJEVI I HIPOTEZE ISTRAŽIVANJA

Ciljevi istraživanja su:

1. ispitati prinose oraha i poljoprivrednih kultura (heljda, ječam, kukuruz) u konsocijacijskim sustavima i u sustavima pojedinačnog uzgoja; odrediti produktivnost svakog sustava
2. ispitati učinkovitost usvajanja vode u sustavu orah – heljda, orah – ječam i orah – kukuruz
3. ispitati utjecaj oraha na mikroklimatske parametre, morfološka svojstva kukuruza i učinkovitost usvajanja hraniva (dušika, fosfora i kalija)
4. kreirati simulacijski model produktivnosti i isplativosti konsocijacije oraha i plodoreda ječam - uljana repica – kukuruz

Iako se očekuje da će prisutnost stabala oraha smanjiti rast i prinose poljoprivrednih kultura, konsocijacijski sustavi trebali bi biti produktivniji od sustava pojedinačnog uzgoja. Također, konsocijacijski sustavi trebali bi imati bolju učinkovitost usvajanja vode i hraniva računajući na pozitivan utjecaj stabala oraha u stvaranju mikroklime i smanjenju evapotranspiracije. S financijskog aspekta, konsocijacija oraha s poljoprivrednim kulturama trebala bi ostvariti veću profitabilnost nego pojedinačni uzgoji, barem u prvih nekoliko godina nakon podizanja nasada.

4. MATERIJAL I METODE RADA

4.1. Dizajn poljskih pokusa

Pokusi su postavljeni na dva lokaliteta tijekom 2019., 2020. i 2021. godine. Na oba lokaliteta primjenjivali su se principi ekološke poljoprivrede. Na svakom od lokaliteta agroklimatološki podaci i uzorci tla i biljnog materijala prikupljeni su s tri parcele: 1) poljoprivredna površina bez drveća, 2) trajni nasadi oraha s usijanom ratarskom kulturom između redova oraha (konsocijacija) te 3) trajni nasadi bez usijane ratarske kulture (voćnjak oraha). Na obje lokacije su stabla cijepljenih oraha, a plodored, tj. rotacija poljoprivrednih kultura u trajnim nasadima i na poljoprivrednoj površini bila je ujednačena i sastojala se od heljde, ječma i kukuruza.

Prvi lokalitet nalazio se u Đakovu, gdje je obradiva oranica veličine 1,05 ha predstavljala kontrolu (samo poljoprivredna kultura), dok je trajni nasad oraha starosti 9 godina (2,7 ha) bio podijeljen na dva dijela gdje se u jednom (1,35 ha) usijavalo poljoprivredne kulture, a drugi dio voćnjaka nije se obrađivao i služio je kao kontrolna parcela za orah. Cjelokupna parcela voćnjaka od 2,7 ha sastojala se od 10 redova oraha s međurednim razmakom od 8 m i razmakom unutar reda 7 m. Ratarske kulture usijavane su unutar prva četiri međureda oraha u širini od 6 m. Pokus na drugom lokalitetu, u Ivankovu, postavljen je po istom principu. Oranica veličine 0,4 ha predstavljala je kontrolu (samo ratarska kultura), dok je parcela trajnih nasada oraha starosti 3 godine (4,35 ha) bila podijeljena na dva dijela gdje se u jednom (cca. 0,6 ha) usijavalo ratarske kulture, a drugi dio parcele bio je samo pod orasima. Cjelokupna parcela voćnjaka od 4,35 ha sastojala se od 14 redova oraha, s međurednim razmakom od 10 m i razmakom unutar reda 10 m. Ratarske kulture usijavane su unutar prva četiri međureda oraha u širini od 8 m.

Na svaku od parcela, na obje lokacije, postavljeni su Tiny Tag data loggeri za praćenje temperature i vlage zraka na visini usjeva. Uz to, postavljene su i meteorološke stanice koje su bilježile količinu oborina, jačinu vjetra i druga klimatska svojstva. Sadržaj vode u tlu praćen je pomoću Watermark senzora koji su također postavljeni na svakoj od parcela.

Uzorkovanje tla za pedološke analize provedeno je svaki put nakon žetve-berbe ratarskih kultura, a analizirana su sljedeća agrokemijska svojstva tla; pH u H_2O (HRN ISO 10390:2005), pH u KCl (HRN ISO 10390:2005), sadržaj organskog ugljika (HRN ISO 14235:1998), hidrolitička kiselost (metoda po Kappenu, JDPZ, 1966), sadržaj karbonata (HRN ISO 10693:2014), koncentracije lakopristupačnog fosfora i kalija (Egner i sur., 1960.) te nitratnog (HRN EN ISO 13395:1998) i amonijačnog dušika (HRN EN ISO

11732:2008). Sva analitika provedena je u ovlaštenom laboratoriju za analizu tla Fakulteta agrobiotehničkih znanosti Osijek.

4.2. Određivanje prinosa i ukupne produktivnosti

Za procjenu prinosa ratarskih kultura ručno je požeta površina od 0,5 m^2 u 10 ponavljanja unutar svake od parcela. Kako bi se odredili prinosi po ukupnoj površini (uključujući površinu koju zauzimaju stabla oraha i neusijanu površinu između njih), prinosi ratarskih kultura po usijanoj površini pomnoženi su s udjelom usjeva u ukupnoj površini; 0,75 za lokaciju Đakovo i s 0,8 za lokaciju Ivankovo. Prinosi oraha određeni su skupljanjem i vaganjem plodova za svaki red stabala posebno, a ukupni prinos po sustavima (konsocijacija i voćnjak bez ratarskih kultura) izražen je u t ha^{-1}, sukladno broju stabala po jedinici površine.

Iz podataka o prinosu oraha i ratarskih kultura, određena je produktivnost svakog od sustava korištenjem LER indeksa (Land Equivalent Ratio) - omjer površine pod pojedinačnim uzgojem i površine pod konsocijacijom koji je potreban da bi se ostvarili jednaki prinosi na istoj razini gospodarenja. LER vrijednosti veće od 1 ukazuju na povećanje produktivnosti po jedinici površine u konsocijacijskom sustavu u odnosu na pojedinačne uzgoje (Ong i Kho, 2015; Mead i Willey, 1980);

$$LER = \frac{Y_{int,A}}{Y_{mono,A}} + \frac{Y_{int,B}}{Y_{mono,B}}$$

$Y_{int,A}$ – prinos oraha u konsocijaciji (kg ha^{-1})

$Y_{mono,A}$ – prinos oraha u voćnjaku (kg ha^{-1})

$Y_{int,B}$ – prinos usjeva u konsocijaciji (kg ha^{-1})

$Y_{mono,B}$ – prinos usjeva na parceli bez oraha (kg ha^{-1})

S obzirom da orah u Ivankovu još ne daje značajne prinose, LER je izračunat samo za sustave u Đakovu.

4.3. Određivanje učinkovitosti usvajanja vode

Iz podataka o prinosu, oborinama i podataka o sadržaju vode u tlu, utvrđena je tzv. produktivnost vode (WP - Water Productivity) u svakom od sustava, a zatim i ukupna učinkovitost usvajanja vode za konsocijacijski sustav (WER - Water Equivalent Ratio).

Prije svega, određena je količina usvojene vode (WU - Water Use) tijekom vegetacije usjeva, što je aproksimacija evapotranspiracije (Hillel, 2003);

$WU = P + S_1 - S_2$ (mm)

P – količina oborina tijekom vegetacije usjeva

S_1 – sadržaj vode u tlu unutar 100 cm dubine na početku vegetacije usjeva

S_2 – sadržaj vode u tlu unutar 100 cm dubine na kraju vegetacije usjeva

Zatim je izračunata produktivnost vode (Water Productivity) WP – omjer prinosa i usvojene vode u pojedinačnim sustavima (Machado i sur., 2008; Sainju i sur., 2021);

$WP = \frac{Y}{WU}$ (kg ha^{-1} mm^{-1})

Y – prinos oraha ili usjeva u pojedinačnom uzgoju ili u konsocijaciji

WU – usvojena voda

Na kraju je bilo moguće odrediti WER – učinkovitost usvajanja vode za cijeli konsocijacijski sustav (Mao i sur., 2012);

$$WER = pWER_A + pWER_B = \frac{WP_{int,A}}{WP_{mono,A}} + \frac{WP_{int,B}}{WP_{mono,B}}$$

$pWER_A$ i $pWER_B$ – parcijalni WER oraha (A) i usjeva (B)

$WP_{int,A}$ i $WP_{int,B}$ – produktivnost vode oraha (A) i usjeva (B) u konsocijaciji

$WP_{mono,A}$ i $WP_{mono,B}$ – produktivnost vode oraha (A) i usjeva (B) u pojedinačnim sustavima

WER vrijednosti veće od 1 ukazuju na učinkovitije korištenje vode u konsocijacijskom sustavu u odnosu na pojedinačne, odnosno, na veću produktivnost (prinose) konsocijacijskog sustava, nego što bi bilo moguće ostvariti u pojedinačnim sustavima s istom količinom usvojene vode.

S obzirom da orah u Ivankovu još ne daje značajne prinose, WER je izračunat samo za sustave u Đakovu.

4.4. Određivanje parametara rasta i prinosa te učinkovitosti usvajanja hraniva kukuruza

Deset biljaka kukuruza nasumično je uzorkovano po širini drvoreda, četiri puta tijekom vegetacije kukuruza: u fazi pet listova (V5), tijekom vodene faze (R2), tijekom voštane faze (R4) i pri žetvi (H). Biljkama je izmjerena visina, a zatim su sušene na 105°C tijekom prva dva sata i na 70°C do konstantne težine kako bi se odredila biomasa nadzemne suhe tvari. Lisna površina biljke određena je zbrajanjem mjerenja maksimalne širine i duljine svakog lista te množenjem s faktorom 0,75 (Yi i sur., 2010). Ova vrijednost je zatim pomnožena s brojem biljaka po 1 m^2 kako bi se dobio indeks lisne površine (LAI). Uređaj SPAD-502 (Soil Plant Analysis Development, Minolta, Japan) korišten je za dobivanje tzv. SPAD vrijednosti zelenila, koje pokazuju relativnu količinu klorofila prisutnog u listovima biljaka. Za procjenu gustoće sklopa, odnosno broja biljaka ručno je požeta površina od 0,5 m^2 u više ponavljanja unutar svake od parcela. Masa 1000 zrna određena je na bazi suhe tvari, a žetveni indeks određen je kao udio suhe mase zrna u ukupnoj suhoj masi.

Za procjenu učinkovitosti usvajanja hraniva u promatranim sustavima kukuruza izračunati su različiti indeksi. Prvo, akumulacija pojedinog hraniva (nutrient accumulation - nA) izračunata je množenjem ukupne nadzemne suhe mase sa sadržajem hraniva kako bi se dobila količina akumuliranih hraniva u kg ha^{-1}. GnA označava količinu hraniva nakupljenu u suhoj tvari zrna. Učinkovitost korištenja hraniva (nutrient use efficiency - nUE) korištena je kao izraz produktivnosti zrna kukuruza po količini usvojenog hraniva (Bridgham i sur., 1995);

$nUE = \frac{Y}{nA}$ (kg ha^{-1} [kg ukupno akumuliranih hraniva $ha^{-1}]^{-1}$)

Y - prinos suhog zrna

nA - akumulacija hraniva, pri čemu n označava dušik, fosfor ili kalij.

Produktivnost hraniva (nutrient productivity - nP) izračunata je kao omjer prinosa zrna i dostupnog sadržaja pojedinog hraniva u tlu (Bridgham i sur., 1995; Schmidt i sur., 2020; Sainju i sur., 2021);

$nP = \frac{Y}{Sn}$ (kg ha^{-1} [kg hraniva u tlu $ha^{-1}]^{-1}$)

Y - prinos suhog zrna

Sn - raspoloživi sadržaj hraniva u tlu, gdje je n N, P ili K.

Indeks mobilizacije hraniva (grain nutrient recovery index - GnRI) korišten je za određivanje učinkovitosti premještanja dostupnih hraniva iz tla u zrno kukuruza (Allen i sur., 2016; Sainju i sur., 2021);

$nRI = \frac{GnA}{Sn}$ (kg akumuliranog hraniva u zrnu ha^{-1} [kg hranivih tvari u tlu ha^{-1}]$^{-1}$)

GnA - akumulacija hraniva u zrnu

Sn - raspoloživi sadržaj hraniva u tlu, gdje je n N, P ili K.

Ovi su indeksi izračunati za tri analizirana makroelementa; dušik (NUE, NP, NRI), fosfor (PUE, PP, PRI) i kalij (KUE, KP, KRI).

4.5. Modeliranje produktivnosti i isplativosti konsocijacijskih sustava s orahom

Za analizu produktivnosti i financijske isplativosti sustava orah i ječam; uljana repica; kukuruz korišteni su simulacijski modeli Yield-SAFE - biofizički model (Van der Werf i sur., 2007) i Farm-SAFE - bioekonomski model (Graves i sur., 2011).

Tri sustava (ratarska kultura bez drveća, konsocijacija ratarskih kultura s orahom i voćnjak oraha) simulirana su na period od 20 godina. Konsocijacija i voćnjak simulirani su u tri scenarija gustoće drveća; 170, 135 i 100 stabala po hektaru, podrazumijevajući razmak između redova od 8, 10 i 12 m. Sukladno tome, širina trake usjeva u konsocijacijskim sustavima iznosila je 6, 8 i 10 m, što je odredilo površine usjeva od 75%, 80% i 83%.

Model je postavljen za lokaciju u Đakovu, s dnevnim vremenskim klimatskim podacima izvedenim iz CliPick modela (Palma, 2017), za razdoblje od 2019. – 2039. CliPick podaci validirani su usporedbom njegovih simuliranih podataka sa zabilježenim podacima s lokalne meteorološke postaje.

Parametarizacija i kalibracija Yield-SAFE modela detaljno je objašnjena u publikacijama van der Werf i sur. (2007) i Graves i sur. (2010). Početna parametarizacija temeljena je na podacima dostupnim iz publikacija Hrvatskog statističkog ljetopisa te osobne komunikacije s poljoprivrednicima, a model je prije svega kalibriran prema poznatim prinosima ratarskih kultura na oranicama bez drveća. Najbolje poklapanje ("best fit") modela s promatranim, odnosno zabilježenim podacima dobiveno je mijenjanjem parametara za količinu transpirirane vode za usjeve i orah, žetvene indekse i dan sjetve. Vrijednosti ovih parametara mijenjane su unutar prihvatljivih raspona određenih literaturom i iskustvima poljoprivrednih proizvođača. Analiza produktivnosti promatranih sustava osim pojedinih prinosa, uključivala je i LER (Land Equivalent Ratio).

Analiza isplativosti svakog od sustava provedena je u Farm-SAFE modelu (Graves i sur., 2011) kalkulacijama troškova i prihoda proizvodnje. Ulazni podaci dobiveni su iz Hrvatske poljoprivredno-šumarske savjetodavne službe (Uprava za stručnu podršku razvoju poljoprivrede i ribarstva) te razgovora s poljoprivrednim proizvođačima. Isplativost promatranih sustava (ratarska kultura bez drveća, konsocijacija ratarskih kultura s orahom i voćnjak oraha) procijenjena je vrijednostima godišnjih neto marži po hektaru za svaki sustav i svaki scenarij gustoće drveća. Za sustave pojedinačnih ratarskih kultura bez drveća oraha i konsocijacijske sustave s orahom, procijenjene su i vrijednosti godišnje neto marže za proizvodnju s nusproizvodima (tj. slamom kukuruza i ječma). Neto marža izračunata je kao razlika prihoda od požnjevenih proizvoda i potpora (Rt) i varijabilnih (Vt) i dodijeljivih fiksnih troškova (At) proizvodnje koji su primjenjivi za svaku godinu (t) tijekom vremenskog razdoblja od T (godina). Ovaj odnos izražen je kao neto sadašnje vrijednosti (net present value - NPV) korištenjem diskontne stope (i) za određivanje sadašnje vrijednosti budućih prihoda;

$$NPV = \sum_{t=0}^{t=T} \frac{(R_t - V_t - A_t)}{(1+i)^t}$$

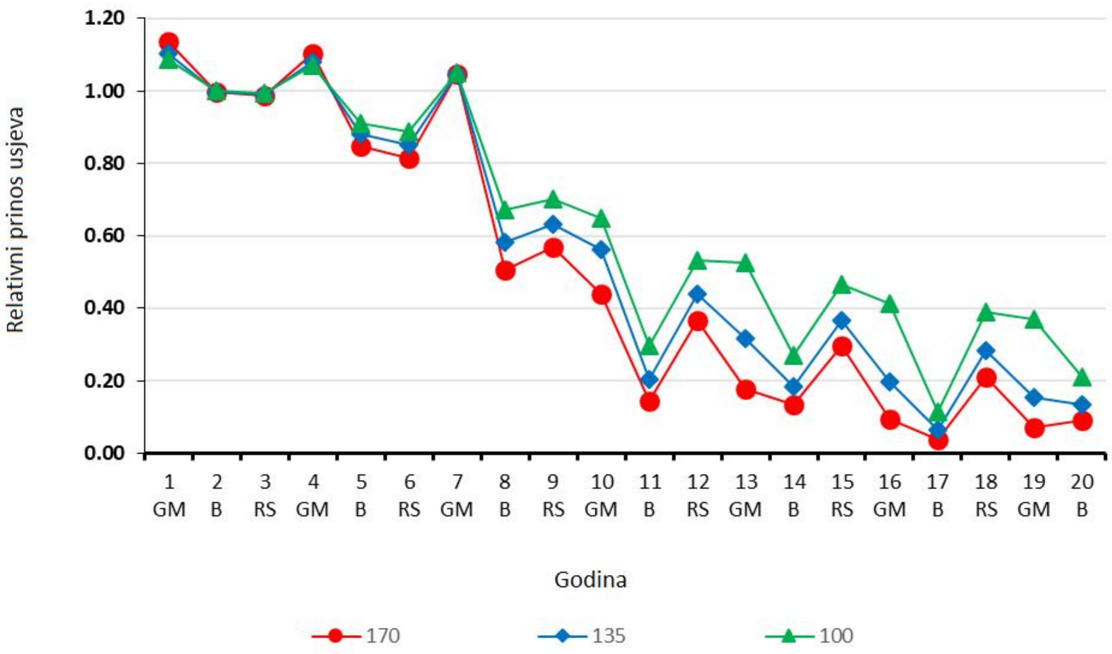
Diskontna stopa (i) od 4% odabrana je prema izvješću Europske komisije 2014., a korištena je u sličnim istraživanjima (Graves i sur., 2007; García de Jalón i sur., 2018). Kumulativne neto marže tijekom simulirane rotacije izračunate su zbrajanjem godišnjih NPV vrijednosti.

5. REZULTATI ISTRAŽIVANJA S RASPRAVOM

5.1. Modeliranje produktivnosti i isplativosti konsocijacijskih sustava s orahom

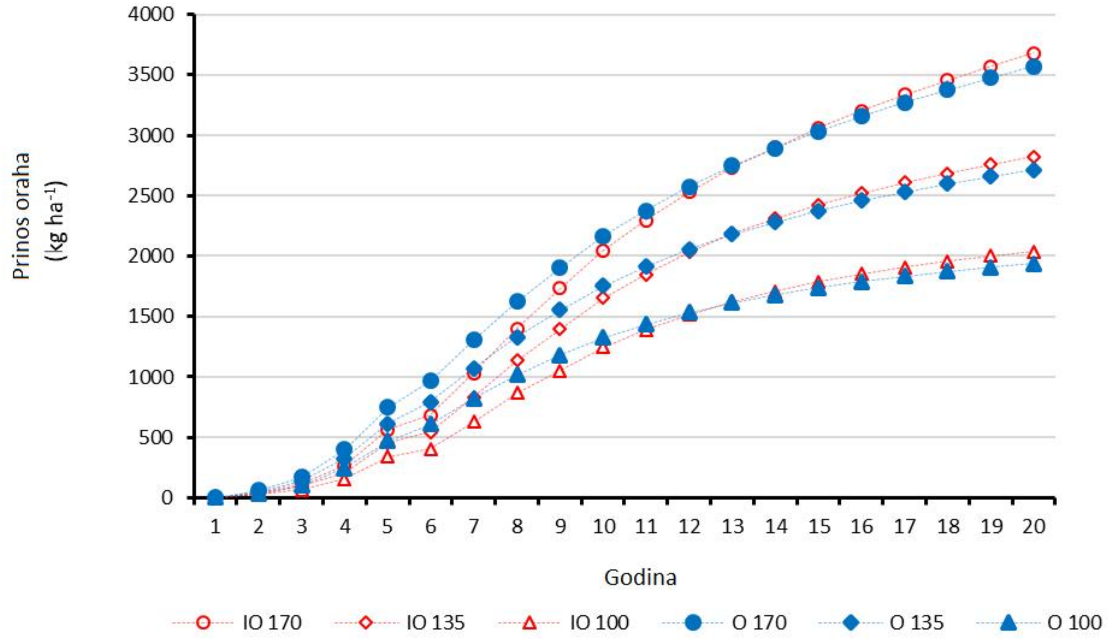
U ovom istraživanju prvi put se koriste bioekonomski modeli u svrhu usporedbe produktivnosti i isplativosti konsocijacijskih sustava ratarskih kultura i drveća uzgajanih u svrhu proizvodnje voća. Dobiveni rezultati prije svega pružaju uvid u mogućnosti uspostave ovakve prakse kao prijelaznog sustava s ratarstva na voćarstvo, ne samo u Hrvatskoj nego i na širem području ovog dijela Europe kojeg karakteriziraju isti klimatski i ekonomski uvjeti.

Visoka korelacija ($r=0,954$, $p<0,05$) utvrđena između prinosa usjeva zabilježenih u stvarnosti i modeliranih Yield-SAFE modelom omogućila je pouzdanost u daljnje korištenje modela u simulacijske svrhe. Model Yield-SAFE predvidio je visoke relativne prinose usjeva (u usporedbi s kontrolom bez drveća) tijekom prvih sedam godina od uspostave konsocijscijskih sustava, osobito za kukuruz, za sva tri scenarija gustoće stabala (Slika 1). Iako neočekivani, takvi prinosi nisu nemogući i o njima su ranije izvijestili i drugi autori (Burgess i sur., 2005; Seserman i sur., 2019). U tradicionalnim Dehesa sustavima u Španjolskoj i Portugalu blizina drveća pokazala je povoljan učinak na rast usjeva (Moreno 2008; Gea-Izquierdo i sur., 2009). Budući da je kukuruz jari usjev, ljetne suše mogu rezultirati smanjenjem prinosa. Međutim, mikroklimatski uvjeti u voćnjacima, u smislu povećane vlažnosti zraka u usporedbi s otvorenim poljem, mogli bi imati povoljan učinak na prinose kukuruza u prvim godinama dok je krošnja oraha mala i nema značajnije zasjene. Također, kukuruz ima dubok i dobro razvijen korijen koji je tijekom prvih nekoliko godina, dok orah nije dosegnuo određeni razvoj, mogao nesmetano apsorbirati dovoljno vode i hraniva iz tla. Unatoč ovim visokim relativnim prinosima kukuruza, model je predvidio stalan pad relativnih prinosa ratarskih usjeva kako su stabla oraha rasla – nakon 7. godine pali su ispod 70% (Slika 1). Unutar modela, ovaj trend se događa zbog sve veće konkurencije za vodu i svjetlo kao posljedica povećanja biomase drveća. Newman (2006) je ostvario slične rezultate u istraživanju sustava s topolom - prinosi ratarskih usjeva mogu se održavati relativno visokima i do 10 godina, sve dok kompeticija za resurse s drvećem ne postane prevelika. Očekivano, simulacije su pokazale da se najveći pad prinosa dogodio pri najvećoj gustoći stabala od 170 stabala ha^{-1}. Slično je pokazano i u istraživanju Graves i sur. (2007) - veće smanjenje relativnih prinosa usjeva zabilježeno je u konsocijacijskim sustavima sa 113 stabala ha^{-1} nego s 50 stabala ha^{-1}.



Slika 1. Simulirani relativni prinosi usjeva u konsocijacijskim sustavima s orahom pri tri scenarija gustoće stabala (170, 135 i 100 stabala po hektaru); GM – kukuruz (Grain Maize); B – ječam (Barley); RS – uljana repica (RapeSeed). Izvor: Žalac i sur., 2021a

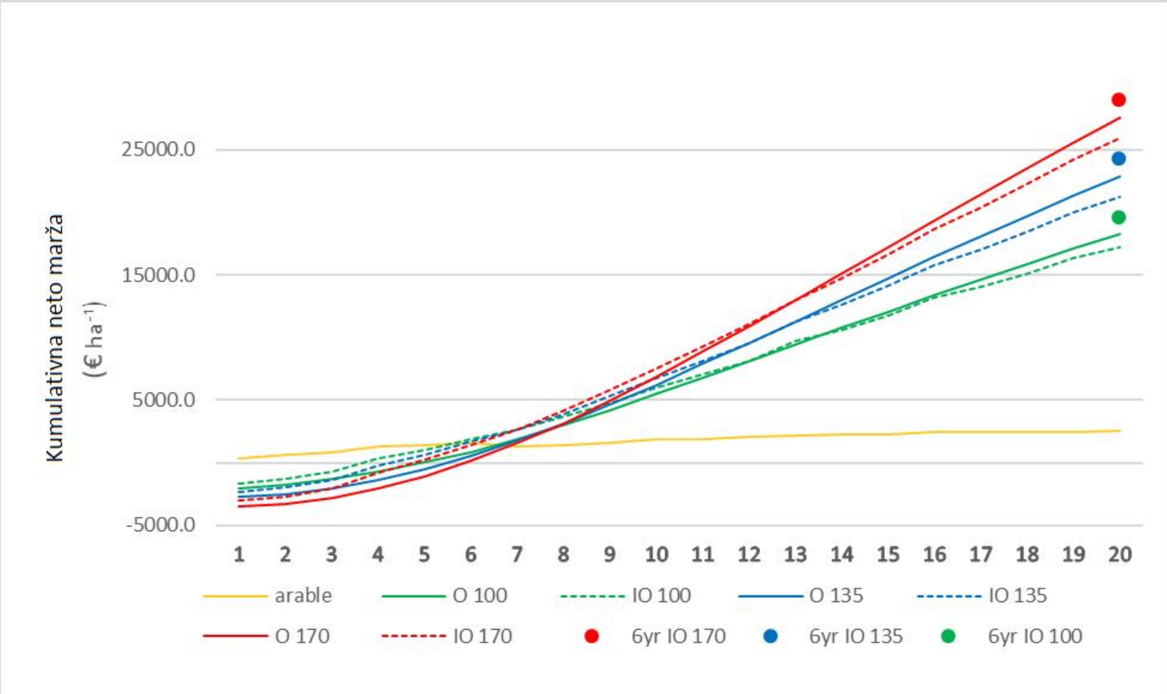
Što se tiče prinosa oraha, Yield-SAFE model je predvidio najveće prinose po hektaru za voćnjak oraha sa 170 stabala po hektaru (3679 kg ha^{-1}), a najmanje za voćnjak sa 100 stabala po hektaru (2038 kg ha^{-1}). Međutim, zbog veće konkurencije među drvećem oraha prinos po stablu bio je najveći u sustavima s 100 stabala po hektaru (kg stabla^{-1}). Graves i sur. (2010) također su izvijestili o sličnim rezultatima - pri velikim gustoćama nasada veća je i konkurencija za svjetlost i vodu, a time i manji rast, odnosno, volumen stabla. Simulacija je također pokazala da bi ratarske kulture u početku smanjile godišnju proizvodnju plodova oraha (Slika 2), najvjerojatnije kompeticijom za vodu, kao što je pokazano i u istraživanju Burgessa i sur. (1996). Ipak, model je pokazao i da s vremenom orah postaje apsolutno dominantnija vrsta u konsocijacijskim sustavima sa sva tri simulirana scenarija, te da usjevi nakon 13. godine više nemaju utjecaj na godišnje prinose oraha. Predviđeno je i da bi prinosi u konsocijacijskim sustavima do 20. godine postali i veći od onih u voćnjacima bez ratarskih usjeva, međutim ta razlika nije bila statistički značajna.



Slika 2. Modelirani prinos plodova oraha pri tri scenarija gustoće stabala (170, 135 i 100 stabala po hektaru); IO – konsocijacijski sustav; O – voćnjak. Izvor: Žalac i sur., 2021a

Dakle, model je predvidio da bi relativni prinosi usjeva u konsocijacijskim sustavima s godinama opadali, dok bi relativni prinosi oraha rasli. Iz ovih relativnih prinosa izračunate su LER vrijednosti koje daju ocjenu produktivnosti simuliranih konsocijacijskih sustava u odnosu na pojedinačne. Iako je model predvidio da bi orasi ostvarili prinose i u prve dvije godine, u stvarnosti se prvi prinosi ostvaruju tek nakon 3. godine. Iz tog razloga su i prve LER vrijednosti simulirane od 3. godine starosti voćnjaka te su iznosile 1,71 u sustavu sa 170 stabala ha^{-1}, 1,68 u sustavu sa 135 stabala ha^{-1} i 1,66 u sustavu sa 100 stabala ha^{-1}. Zbog drastičnog pada relativnih prinosa usjeva, LER vrijednosti su također znatno opadale te su na kraju simuliranih 20 godina iznosile: 1,38 u sustavu sa 170 stabala ha^{-1}, 1,43 u sustavu sa 135 stabala ha^{-1} i 1,53 u sustavu sa 100 stabala ha^{-1}. Ipak, sve vrijednosti upućuju na prednost simuliranih konsocijacijskih sustava u produktivnosti po jedinici površine, u odnosu na pojedinačno uzgajan orah i usjeve, te su u skladu s dosadašnjim istraživanjima provedenim u Europi (Graves i sur., 2007).

Financijska analiza pokazala je da je obradivi sustav ratarskih kultura bez drveća davao pozitivne i relativno dosljedne prihode tijekom 20 godina. Početni troškovi podizanja nasada oraha bili su 1600–3500 € ha^{-1}, ovisno o gustoći stabla, zbog čega su konsocijacijski sustavi i voćnjaci oraha počeli sa značajnim gubicima, koji su nadoknađeni tek kada je orah počeo davati značajnije prinose (Slika 3). Model je predvidio da bi usjevi povećali isplativost konsocijacijskih sustava tijekom prvih 6 godina starosti oraha, međutim, nastavak usijavanja nakon tog razdoblja rezultirao je financijskim gubicima jer usjevi nisu mogli postići zadovoljavajuće prinose i prihode. U praksi, čim bi proizvodnja usjeva postala neprofitna, poljoprivrednik bi prestao s usijavanjem. Takvi scenariji s prekinutim usijavanjem u 7. godini rezultirali su većom neto maržom nakon 20 godina, u odnosu na voćnjake oraha bez usjeva, za sve tri gustoće (Slika 3), što je pokazalo da je praksa usijavanja ratarskih kultura u voćnjake oraha isplativa opcija za prijelaz s ratarstva na proizvodnju oraha. Međutim, ostaje sporno je li ova razlika u financijskoj dobiti dovoljna da bi se poljoprivredni proizvođači odlučili na praksu usijavanja.



Slika 3. Kumulativne neto marže obradivog sustava usjeva bez drveća (arable) te voćnjaka oraha (O) i konsocijacijskih sustava (IO) s gustoćama stabala od 170 stabala ha^{-1}, 135 stabala ha^{-1} i 100 stabala ha^{-1} - tijekom 20 godina i konsocijacijski sustavi s prekinutim usijavanjem nakon 6. godine (6yr IO). Izvor: Žalac i sur., 2021a

Ova se analiza usredotočila isključivo na agronomsku i financijsku analizu sustava. U praksi, dodatak drveća na obradivim površinama pruža i ekološke koristi kao što su povećano skladištenje ugljika, smanjeno onečišćenje voda i povećana bioraznolikost, čemu se mogu pripisati i financijske vrijednosti (García de Jalón i sur., 2018).

5.2. Produktivnost i učinkovitost usvajanja vode u konsocijacijskim sustavima s orahom (heljda i ječam)

Prethodno istraživanje pokazalo je da bi konsocijacijski sustavi mogli biti isplativo prijelazno rješenje za poljoprivrednike koji imaju za cilj preći s ratarstva na proizvodnju oraha. Osim toga, usijavanje ratarskih kultura među redove oraha pruža dodatne mogućnosti zarade i za voćare već zrelih voćnjaka. Međutim, veći ulozi i rad koji treba primijeniti u ovakvim sustavima predstavljaju rizik zbog neizvjesnosti o produktivnosti različitih usjeva na koje značajno utječu zrela stabla oraha. Ovo istraživanje imalo je za cilj istražiti ekološke aspekte takvih sustava, odnosno koliko produktivni i učinkoviti u usvajanju vode mogu biti heljda (jari usjev) i ječam (ozimi usjev) pod starijim nasadom oraha s užim razmakom među redovima (Đakovo), za razliku od mlađeg, sa širim (Ivankovo).

Velike razlike zabilježene su s obzirom na usjev, ali i starost/gustoću drveća oraha. Naime, u odnosu na referentne pojedinačne sustave, prinos i produktivnost vode heljde pokazali su se znatno boljim u mladom voćnjaku, dok je ječam bio uspješniji u starijem (Tablica 1; Tablica 2). Sustav oraha i heljde u Đakovu postigao je prosječni LER od 1,05 i WER od 1,12 (Tablica 1; Tablica 2). Međutim, ako uzmemo u obzir odstupanja od ovih srednjih vrijednosti, nije moguće zaključiti da je ova kombinacija produktivnija po jedinici površine i usvojene vode od pojedinačnih sustava oraha i heljde. Stabla oraha u konsocijacijskom sustavu proizvela su samo 51% prinosa voća u usporedbi s voćnjakom oraha bez ratarskih usjeva. Međutim, ovaj dio voćnjaka uvijek je imao manje prinose, čak i prije usijavanja ratarskih kultura, stoga nije moguće pripisati definitivan učinak heljde ovim rezultatima.

Tablica 1. Produktivnost konsocijacijskih sustava (Land Equivalent Ratio – LER)

Lokacija	Usjev	$pLER_C$	$pLER_W$	LER
Đakovo	Heljda	0,54 ± 0,09 b	0,51	1,05 ± 0,09 b
	Ječam	0,72 ± 0,18 b	0,81	1,53 ± 0,18 a
Ivankovo	Heljda	1,17 ± 0,43 a	-	-
	Ječam	0,63 ± 0,13 b	-	-

Izvor: Žalac i sur., 2022. *srednje vrijednosti označene različitim slovima ukazuju na statistički značajne razlike između sustava ($P<0,05$; Tukey HSD test). Razlike između $pLER_C$ vrijednosti (relativni prinosi usjeva) testirane su za oba usjeva zajedno, a LER vrijednosti za Đakovo uspoređene su između dvije godine. Razlike između $pLER_W$ nisu statistički uspoređivane jer su zabilježeni samo ukupni prinosi.

Tablica 2. Produktivnost vode u promatranim sustavima

Godina/ usjev	Lokacija	Sustav	WP (kg ha^{-1} mm^{-1})	pWER	WER
2019 Heljda	Ivankovo	Usjev - kontrola	3,38 ± 1,73 b	1,19 ± 0,44 a	-
		Usjev - konsocijacija	4,04 ± 1,48 b		
	Đakovo	Usjev - kontrola	6,68 ± 1,13 a	0,57 ± 0,10 b	1,12 ± 0,10 b
		Usjev - konsocijacija	3,81 ± 0,68 b		
		Orah - voćnjak	1,94	0,55	
		Orah - konsocijacija	1,07		
2020 Ječam	Ivankovo	Usjev - kontrola	15,34 ± 3,73 b	0,60 ± 0,13 b	-
		Usjev - konsocijacija	9,25 ± 1,96 c		
	Đakovo	Usjev - kontrola	31,32 ± 3,13 a	0,93 ± 0,23 a	1,83 ± 0,23 a
		Usjev - konsocijacija	28,99 ± 7,30 a		
		Orah - voćnjak	12,76	0,90	
		Orah - konsocijacija	11,45		

Izvor: Žalac i sur., 2022. *srednje vrijednosti označene različitim slovima ukazuju na statistički značajne razlike između sustava ($P<0,05$; Tukey HSD test). Razlike između WP vrijednosti testirane su za svaki usjev zasebno, između $pWER_C$ vrijednosti za oba usjeva zajedno, a WER vrijednosti za Đakovo uspoređene su između dvije godine. Razlike između $pWER_W$ nisu statistički uspoređivane jer su zabilježeni samo ukupni prinosi.

Tijekom vegetacije heljde u Đakovu zabilježeni su suhi hidrotermički uvjeti. Neka istraživanja sugeriraju da zasjenjivanje krošnjom stabala može ublažiti nepovoljne učinke suše smanjenjem toplinskog stresa (Li i sur., 2010; Sida i sur., 2018; Arenas-Corraliza i sur., 2019), smanjenjem evaporacije, odnosno gubitka vode iz tla i time očuvanjem većih količina vode za transpiraciju biljaka (Rivest i Vézina, 2014). Iako je konsocijacijski sustav vjerojatno smanjio evaporaciju, rezultati ukazuju na to da je ovaj učinak bio zanemariv jer visoke potrebe heljde za vodom, posebno tijekom faze klijanja i cvjetanja, nisu zadovoljene u konsocijacijskom sustavu sa starijim orasima, gdje je kompeticija za vodu bila prejaka. Sušni stres tijekom ovih kritičnih faza razvoja heljde ima veliki utjecaj na smanjenje broja cvjetova i, posljedično, broja sjemenki i ukupnog prinosa po jedinici površine (Slawinska i Obendorf, 2001). Osim toga, zasjena velikim krošnjama oraha vjerojatno je uzrokovala i stres zbog nedostatka svjetlosti i imala negativan učinak na prinos heljde.

Suprotno, u Ivankovu, gdje su orasi posađeni na šire razmake te njihova manja krošnja ne stvara značajnu zasjenu, heljda je postigla veći prinos i produktivnost po jedinici usvojene vode u konsocijacijskom sustavu nego na parceli bez drveća (kontroli) (Tablica 1; Tablica 2). Općenito, Ivankovo je imalo povoljnije klimatske i hidrološke uvjete tijekom vegetacije heljde, a konkurencija između stabala i usjeva zanemariva je ukoliko je sadržaj vode dostatan (Zhao i sur., 2011; Bayala i Prieto, 2019). Naši rezultati sugeriraju da mlada stabla oraha u Ivankovu nisu ometala heljdino usvajanje vode, za razliku od rezultata zabilježenih u Đakovu. Osim toga, veći sadržaj vode u konsocijacijskom sustavu nego u pojedinačnim sustavima heljde i oraha, implicira da su heljda i stabla oraha učinkovito dijelili vodu koja bi se inače izgubila iz tla evaporacijom. Ipak, nije moguće opisati mehanizam iza komplementarnih interakcija u ovom sustavu bez detaljnijeg istraživanja procesa u tlu i distribucije korijena.

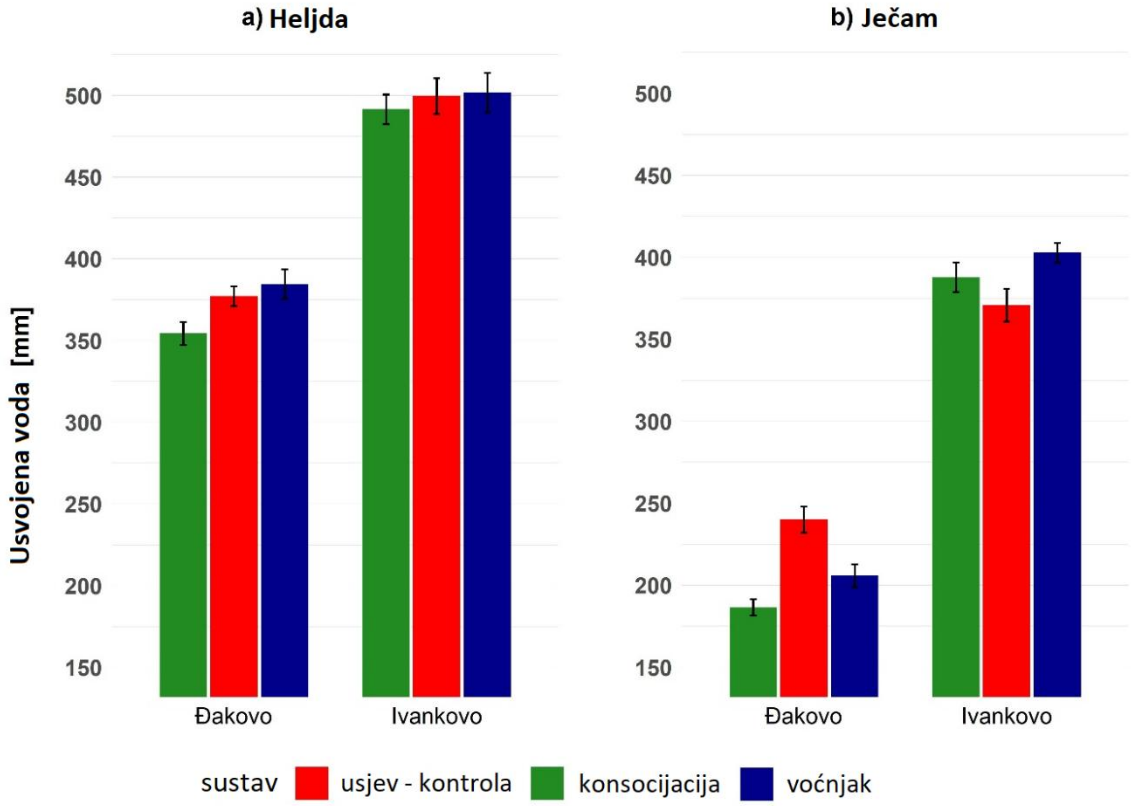
Zbog visokih relativnih prinosa usjeva i oraha, konsocijacijski sustav oraha i ječma u Đakovu postigao je visoke LER i WER vrijednosti (Tablica 1; Tablica 2). Naši su rezultati pokazali da je ovaj sustav bio u prosjeku 53% produktivniji po jedinici površine i 83% produktivniji po jedinici usvojene vode od zasebnih sustava, a također je bio i 47% produktivniji po jedinici površine i 71% produktivniji po jedinici usvojene vode od sustava orah–heljda. Razlika između prinosa oraha u voćnjaku i konsocijacijskom sustavu nije bila toliko velika u 2020. godini. Poboljšani $pLER_W$(0,81) i $pWER_W$(0,90) oraha pokazuju da ili suptilne promjene u svojstvima tla pozitivno utječu na produktivnost oraha ili možda postoji neki mehanizam pozitivnog učinka ječma.

U teoriji, između zimskih usjeva i stabala oraha može postojati vremenska komplementarnost u korištenju resursa. Naime, orah je listopadna vrsta koja relativno kasno lista, pa zasjena njegovom krošnjom tijekom kasnijeg razvoja ječma vjerojatno nema kritičan ograničavajući učinak na prinos. Nadalje, ječam je C3 biljka, što znači da je manje osjetljiv na negativne učinke zasjenjivanja jer je dovoljno samo 50% pune sunčeve svjetlosti da biljka postane potpuno zasićena svjetlom (Reynolds i sur., 2007). Također, intenzivniji rast korijenovih dlačica oraha doseže vrhunac tijekom ljetnih mjeseci (Germon i sur., 2015; Mohamed i sur., 2019), a do kad većina zimskih usjeva, uključujući ječam, dosegne gotovo potpuni razvoj i usvoji većinu hranivih tvari i vode iz tla (Burgess i sur., 2005). U prilog ovoj hipotezi o vremenskoj komplementarnosti govore rezultati istraživanja Liu i sur. (2019). Autori su pokazali da orah najviše vode troši u fazi intenzivnog razvoja ploda tijekom ljetnih mjeseci, a izvori te vode su uglavnom dublji slojevi tla.

Iako je sadržaj vode u tlu tijekom sjetve i žetve bio veći u konsocijaciji nego na kontrolnoj parceli bez drveća, nepoznato je kako je voda bila raspodijeljena kroz vegetaciju i kako je podijeljena između ječma i oraha.

Ipak, prinos ječma i produktivnost po jedinici usvojene vode u konsocijacijskim sustavima na obje lokacije bili su niži nego u njihovim pojedinačnim sustavima. Osim toga, $pLER_C$ i $pWER_C$ ječma niži su u Ivankovu nego u Đakovu (Tablica 1; Tablica 2). Zasjena većim krošnjama drveća u Đakovu vjerojatno je imala utjecaj na produktivnost ječma. Međutim, u Ivankovu, gdje su stabla oraha široko razmaknuta, a manje krošnje ne stvaraju značajnu sjenu, konkurencija za vodu i hranive tvari vjerojatno je bila glavni čimbenik produktivnosti sustava oraha i ječma, a može se povezati s uzorkom ukorjenjivanja. Općenito, potrošnja vode drveća raste sa starošću stabla, tako da korijenski sustav ima tendenciju rasti u dubinu kako bi zadovoljio sve veće potrebe za vodom (Song i sur., 2016). U skladu s tim, mlađa stabla preferiraju crpiti vodu iz plićih slojeva tla, gdje im je većina korijena (Upson i Burgess, 2013). Posljedično, u mlađim konsocijacijskim sustavima može postojati jača kompeticija za vodu i hranive tvari i time uzrokovati značajnije smanjenje prinosa usjeva. Zhao i sur. (2011) primijetili su da je većina bočnog korijenja četverogodišnjih stabala žižule bila razvijena do 30 cm dubine tla, dok su starija stabla žižule imala većinu svojih bočnih korijena na oko 60 cm dubine tla. To je moglo uzrokovati zabilježeno veće smanjenje prinosa kikirikija ispod mlađih stabala žižule. Nadalje, tlo u Ivankovu ima veću gustoću tla, te je općenito zbijenije od tla u Đakovu, posebice u podoraničnom sloju. Takvo tlo može ograničiti vertikalni rast korijena drveća i uzrokovati izraženije bočno širenje korijena, što onda negativno utječe na razvoj korijena usjeva i njegovo usvajanje vode i hranivih tvari. S druge strane, s obzirom na ovu hipotezu i visok prinos heljde u konsocijacijskom sustavu u Ivankovu, čini se da korijenje heljde, unatoč maloj ukupnoj masi, ima dobru apsorpcijsku moć (Gondola i Papp, 2010) i osigurava visoku produktivnost, čak i u konkurenciji s mladim stablima oraha.

Konsocijacijski sustav oraha i ječma u Ivankovu usvojio je više vode od sustava zasebno uzgajanog ječma i mnogo više od oba sustava s ječmom u Đakovu (Slika 4). Točnije, WU vrijednosti bile su konstantno veće u Ivankovu nego u Đakovu, a te se razlike djelomično mogu objasniti razlikama u količini oborina i drugim klimatskim uvjetima. Nadalje, rezultati su pokazali da je smanjenje utroška vode (tj. ETC) u konsocijacijskim sustavima, u usporedbi s pojedinačnim, bilo izraženije u Đakovu (Slika 4).

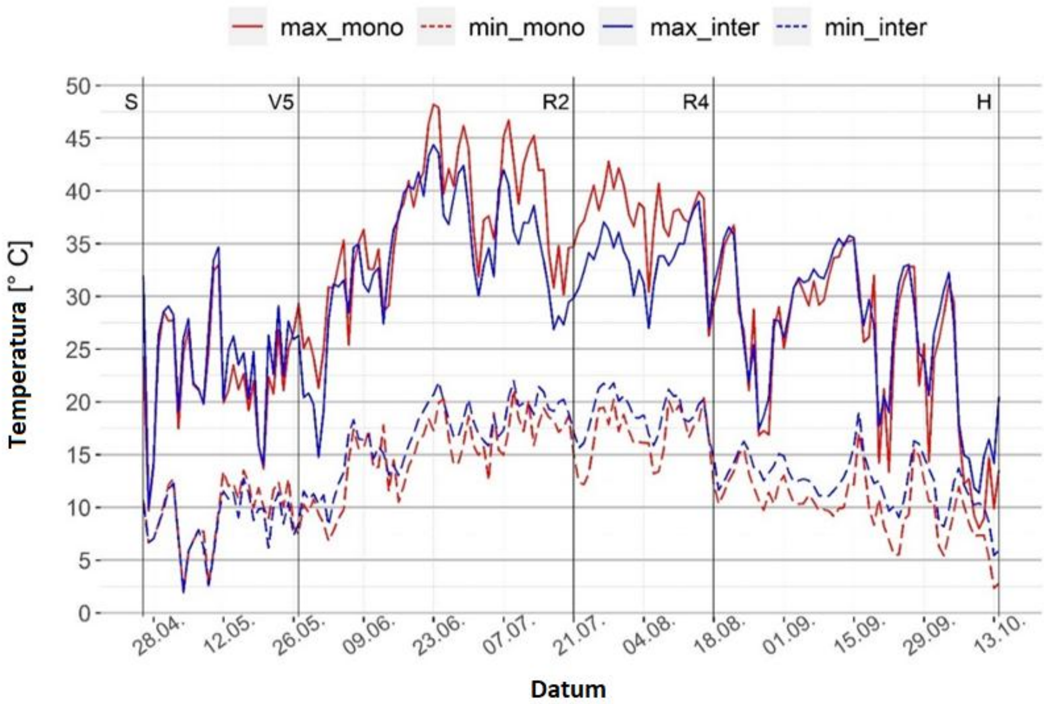


Slika 4. Količina usvojene vode, odnosno evapotranspiracije, u promatranim sustavima tijekom vegetacije a) heljde i b) ječma. Okomite linije predstavljaju standardnu devijaciju od srednjih vrijednosti. Izvor: Žalac i sur., 2022.

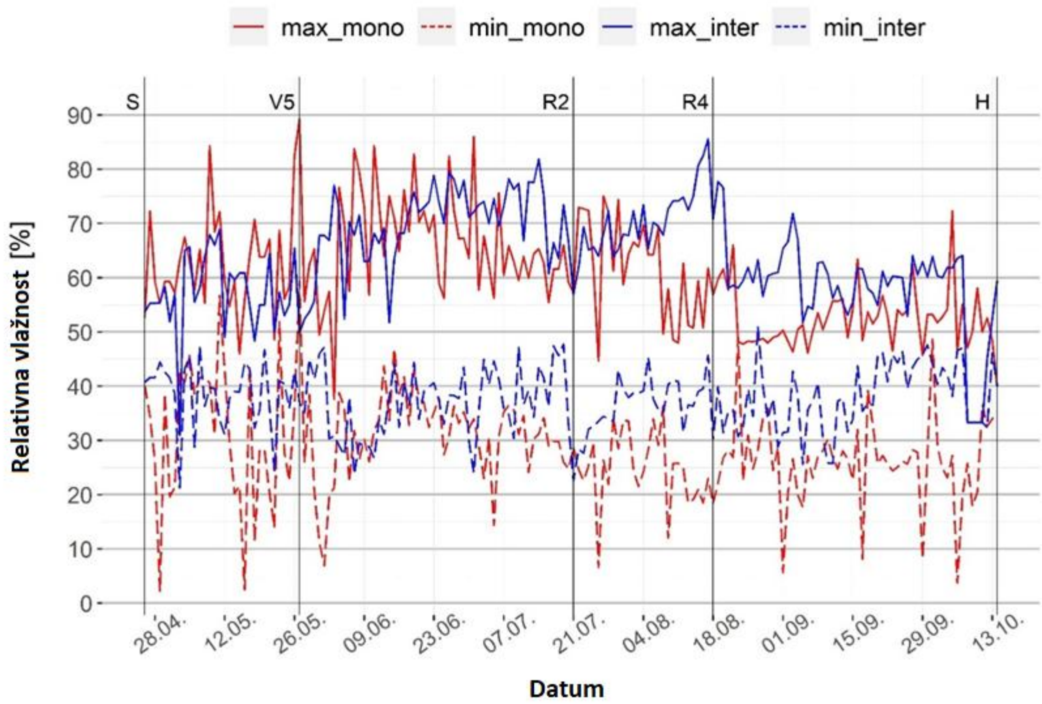
Liu i sur. (2018) utvrdili su da gusta krošnja topole u konsocijacijskom sustavu smanjuje sunčevu radijaciju i brzinu vjetra, što dovodi do većeg udjela transpiracije biljaka, a manjeg udjela evaporacije iz tla u ukupnoj evapotranspiraciji. Iako razlika između transpiracije biljaka i evaporacije vode iz tla nije procijenjena u ovom istraživanju, uzimajući u obzir ova opažanja kao i prethodna istraživanja, čini se da je zasjena većim krošnjama stabala oraha u Đakovu doprinijela smanjenju evaporacije (Wallace i sur., 1999). Dodatno, veća evapotranspiracija primijećena je tijekom vegetacije heljde, što se može pripisati toplijim ljetnim uvjetima i većoj stopi transpiracije stabala zbog povećanog rasta oraha tijekom ovih mjeseci.

5.3. Ekološke i agronomske prednosti usijavanja kukuruza u voćnjak oraha

Različiti simulacijski modeli za buduću klimu u Europi predviđaju toplije i suše uvjete s povećanim rizikom od toplinskog stresa i suše tijekom ljeta, posebno za panonsku regiju (Trnka i sur., 2011; Giorgi i Lionello, 2008). U usporedbi s prosječnim mjerenjima za našu regiju u razdoblju od 1981. do 2010., travanj i svibanj 2021. bili su znatno hladniji od normale (DHMZ, 2022), a ljetni mjeseci 2021. bili su relativno topli i suhi. Tijekom vegetacije kukuruza palo je samo 327,5 mm kiše, koja nije bila ravnomjerno raspoređena. Najveći manjak oborine dogodio se tijekom lipnja 2021. Međutim, primiječen je pozitivan utjecaj konsocijacijskog sustava na promjene u mikroklimatskim uvjetima. Općenito, ovaj je sustav imao nižu maksimalnu i višu minimalnu temperaturu i vlažnost od kontrolne parcele kukuruza bez drveća (Slika 5; Slika 6), što znači da je bilo manje oscilacija na dnevnoj bazi, što može pomoći biljkama da se prilagode i odupru stresnim uvjetima. Tijekom prvih mjesec dana od sjetve kukuruza nije bilo značajne razlike u ekstremnim dnevnim temperaturama između dva promatrana sustava, budući da tada orah tek počinje razvijati lišće i još ne uzrokuje značajno zasjenjivanje. Međutim, utvrđene su značajne razlike u pogledu maksimalnih i minimalnih dnevnih temperatura tijekom razdoblja od faze pet listova kukuruza (V5) do voštane faze (R4), te minimalnih temperatura od voštane faze (R4) do berbe, odnosno žetve (H), kada je konsocijacijski sustav imao značajno niže maksimalne i više minimalne temperature, pružajući stabilnije uvjete ($p<0,05$; Tukey) (Slika 5). Što se tiče dnevne relativne vlažnosti zraka, analizom varijance utvrđena je statistički značajna razlika između dva sustava tijekom svih faza rasta kukuruza, odnosno cijele vegetacije. Konsocijacijski sustav imao je višu maksimalnu i minimalnu relativnu vlažnost, osim tijekom prvog mjeseca rasta kukuruza kada je parcela bez drveća imala višu maksimalnu vlažnost ($p<0,05$; Tukey HSD) (Slika 6). Ove pozitivne promjene u mikroklimi uglavnom su bile posljedica zasjene i smanjenja vjetra, čime se smanjuje temperatura i povećava vlažnost zraka, a konačni rezultat je i smanjenje evapotranspiracije (Temani i sur., 2021). Slični rezultati dobiveni su i u drugim istraživanjima konsocijacijskih sustava s drvećem u različitim regijama (Karki i Goodman, 2014; Gosme i sur., 2016; Kanzler i sur., 2019; Panozzo i sur., 2022).



Slika 5. Dnevni raspon temperature (minimum i maksimum) unutar redova kukuruza na parceli bez drveća (min_mono i max_mono) i u konsocijaciji s orahom (min_inter i max_inter). S – sjetva; V5 – faza 5 listova; R2 – vodena faza; R4 – voštana faza; H – žetva. Izvor: Žalac i sur., 2023.



Slika 6. Dnevni raspon relativne vlažnosti zraka (minimum i maksimum) unutar redova kukuruza na parceli bez drveća (min_mono i max_mono) i u konsocijaciji s orahom (min_inter i max_inter). S – sjetva; V5 – faza 5 listova; R2 – vodena faza; R4 – voštana faza; H – žetva. Izvor: Žalac i sur., 2023.

Sadržaj vode u tlu na početku i na kraju vegetacije kukuruza bio je podjednak u sva tri promatrana sustava. U travnju stabla oraha još nisu prolistala, a u listopadu su već izgubila većinu lišća. Sukladno tome, orahova potreba za vodom u tim razdobljima nije velika i njegovo usvajanje vode ne utječe značajno na sadržaj vode u tlu. Tijekom faze V5 najviše vode sačuvano je u konsocijacijskom sustavu, ali kasnije u vegetaciji, ovaj je sustav imao mnogo manje vode od kukuruza na zasebnoj parceli i to posebno u dubljim slojevima tla, što bi mogao biti pokazatelj uzorka orahovog usvajanja vode. Pozitivni učinci drveća na mikroklimu u smislu sniženih dnevnih temperatura, povećane vlažnosti zraka i niže transpiracije biljaka u sjeni mogu osigurati i veći sadržaj vode u tlu smanjenjem njegovog gubitka. Ovaj ishod utvrđen je u istraživanju Panozzo i sur. (2022) provedenom u južnoj Francuskoj - uočena je veća dostupnost vode u sustavu maslina-pšenica nego na kontrolnoj parceli pšenice, a te su razlike bile najizraženije tijekom posljednjeg razdoblja vegetacije pšenice (svibanj i lipanj). Iako su i u ovom istraživanju uočene slične promjene mikroklime (Slika 5; Slika 6) i veći sadržaj vode u konsocijacijskom sustavu tijekom kasnog svibnja (V5 faza), kompeticija za vodu između stabala oraha i kukuruza značajno se povećala tijekom suhih ljetnih mjeseci, što je dovelo do većeg pada u sadržaju vode u tlu nego na kontrolnoj parceli kukuruza. Ova opažanja nisu bila neočekivana s obzirom na manjak oborina i visoke temperature zabilježene u ovom razdoblju, ali također, u ovom razdoblju orahove potrebe za vodom su na vrhuncu zbog intenzivnog rasta ploda (Liu i sur., 2019) i korijenovih dlačica (Germon i sur., 2015; Mohamed i sur., 2019).

Kemijska svojstva tla pokazala su da se tlo u konsocijacijskom sustavu nije značajno razlikovalo od tla u voćnjaku oraha, osim manjeg sadržaja kalija. Razlike u svojstvima tla između konsocijacijskog sustava i kontrolne parcele kukuruza pokazale su se ponajviše u pH i sadržaju organske tvari, koji su bili značajno viši u konsocijacijskom sustavu ($p<0,05$; Tukey HSD). Brojna istraživanja potvrdila su značajan doprinos sustava temeljenih na drveću u sekvestraciji ugljika u tlu (Pandey, 2002; Peichl i sur., 2006; Weerasrekara i sur., 2016; Cardinael i sur., 2017), koji doprinosi većem sadržaju ugljika u tlu i većoj nadzemnoj biomasi nego u tradicionalnim poljoprivrednim sustavima bez drveća (Oelbermann i sur., 2004; Muchane i sur., 2020). Organski ugljik glavna je komponenta organske tvari tla, a nalazi se u većem sadržaju u sustavima s drvećem zbog većih inputa organske tvari u vidu lišća i korijenja te zbog smanjenja temperature tla zasjenjivanjem (Chander i sur., 1998; Pinho i sur., 2012). S druge strane, niži sadržaj organske tvari u konsocijacijskim sustavima u usporedbi s voćnjacima mogao bi biti posljedica obrade tla (Sainepo i sur., 2018), iako ta razlika u našem slučaju nije bila značajna.

Što se tiče svojstava rasta kukuruza mjerenih tijekom vegetacije, uočene su statistički značajne razlike u korist kukuruza u konsocijacijskom sustavu, unatoč uočenoj konkurenciji za vodu s orahom. Tijekom cijele vegetacije, kukuruz u konsocijacijskom sustavu bio je višlji od kukuruza na kontrolnoj parceli, te je imao veći indeks lisne površine (LAI) i veće SPAD vrijednosti. U početku vegetacije imao je i veću nadzemnu biomasu (do stadija R4) (Tablica 3). Svi ovi rezultati bili su znakovi prilagodbe kukuruza na zasjenjene uvjete - biljke koje rastu u sjeni imaju tendenciju izraženog rasta u visinu i stvaranja veće lisne površine kako bi dosegle više svjetla (Lee i sur., 1995; Irving, 2015; Weselek i sur., 2021). Iako je dolazno fotosintetski aktivno zračenje glavni čimbenik proizvodnje suhe tvari biljaka, učinkovitost fotosinteze uvjetovana je i lisnom površinom biljke, gustoćom lisne površine i trajanjem lisne površine (Lawlor, 1995; Monteith, 1972), zbog čega usjevi u konsocijacijskim sustavima ne moraju nužno imati smanjenu fotosintezu. Gillespie i sur. (2000) nisu uočili utjecaj zasjene drveća na neto fotosintezu kukuruza, dok su Zhang i sur. (2018) otkrili su da je neto fotosintetska učinkovitost na razini lišća usjeva u konsocijaciji bila čak i viša nego u sustavu bez drveća zbog povećanja udjela difuznog zračenja. Ranija istraživanja na pokusnim sustavima sa voćnjakom oraha u istom dizajnu kao i u ovom istraživanju, pokazala su da sunčevo zračenje ispod krošnje tijekom ljetnih mjeseci ne pada ispod 10 000 luksa, što je dovoljno za normalan rast biljaka (Ivezić i sur., 2021). Veća nadzemna biomasa kukuruza u konsocijaciji povezana je s povećanom visinom i površinom lista. Međutim, u takvim slučajevima smanjena je količina ugljika ugrađenog u stabljiku (Irving, 2015). Čini se da je to mogao biti slučaj i u ovom istraživanju - na kraju vegetacije, kada je lišće ostarjelo i počelo se raspadati, kukuruz na kontrolnoj parceli imao je veću nadzemnu biomasu zbog više suhe tvari u stabljici (Tablica 3). Drugi slučaj bi mogao biti da je kukuruz na kontrolnoj parceli zbog nepovoljnih mikroklimatskih uvjeta produžio alokaciju ugljika u vegetativne organe, umjesto u zrno.

Tablica 3. Svojstva kukuruza mjerena tijekom: V5 – faza 5 listova; R2 – vodena faza; R4 – voštana faza; H – žetva

	Sustav	V5	R2	R4	H
Visina [cm]	kontrola	22,9 b	181,8 b	206,4 b	180,0 b
	konsocijacija	36,0 a	220,1 a	229,8 a	223,0 a
Nadzemna biomasa [kg ha^{-1}]	kontrola	26,5 b	7191,3 b	13856,1 a	21918,1 a
	konsocijacija	36,0 a	10589,4 a	16838,3 a	17768,4 b
LAI [m2 m^{-2}]	kontrola	0,07 b	3,00 b	3,21 b	-
	konsocijacija	0,13 a	3,47 a	4,94 a	-
SPAD	kontrola	31,19 b	40,47 b	49,44 b	-
	konsocijacija	33,68 a	57,06 a	55,45 a	-

Izvor: Žalac i sur., 2023. *srednje vrijednosti označene različitim slovima ukazuju na statistički značajne razlike između sustava ($P<0,05$; Tukey HSD test)

Tabolt i sur. (2014) tvrde da je zasjena ključni čimbenik za prinose usjeva u sustavima s drvećem. Učinak zasjene ovisi o mnogim drugim čimbenicima, a jedan od njih je vrsta drveća, odnosno struktura njegove krošnje. Reynolds i sur. (2007) utvrdili su da je sjena od stabala topola utjecala na rast i prinos kukuruza u većoj mjeri nego sjena od stabala srebrnog javora, što je određeno razlikama u visini i strukturi krošnje između ove dvije vrste drveća. Iznenađujuće, Rao et al. (1998) otkrili su da je na prinos kukuruza pozitivno utjecala zasjena *Peltophoruma*, spororastućeg stabla s malom krošnjom. Okrugla, nepravilna, poluotvorena krošnja stabala oraha odgovara kriterijima dobre drvenaste vrste za konsocijacijske sustave (Tengnas, 1994). Orijentacija redova također igra važnu ulogu. Osim ako se krošnje stabala međusobno spajaju i preklapaju, sjeverno-južna (S-J) orijentacija reda uzrokuje manju zasjenu na sredinu međureda nego istočno-zapadna (I-Z) orijentacija, posebno na višim geografskim širinama. Kod S-J orijentacije, sjene drveća u podne, kada se odvija većina fotosinteze u biljkama, leže uglavnom ispod redova drveća, a ne na redovima usjeva (Reynolds i sur., 2007; Dufour i sur., 2012; Artru i sur., 2016). Iako je razvoj kukuruza u konsocijaciji bio potaknut smanjenom dostupnošću svjetla, uzimajući u obzir sve navedeno, zasjena ipak nije imala ključnu ulogu u smanjenju prinosa kukuruza u našem istraživanju. Glavni čimbenik značajno smanjenog prinosa kukuruza po ukupnoj površini u konsocijaciji bila je značajno manja gustoća biljaka kukuruza (Tablica 4). U prethodnim istraživanjima u istom voćnjaku oraha, utvrđeno je da je gustoća usjeva uvijek bila manja u konsocijaciji nego na kontrolnim parcelama; kod pšenice za 16%, ječma za 13%, a heljde za 29%. Manja gustoća biljaka, odnosno smanjena klijavost u konsocijaciji s orahom mogla bi biti povezana s alelopatskim svojstvima oraha, točnije izlučivanjem juglona u tlo (Islam i Widhalm, 2020). Juglon (5-hidroksi-1,4-naftokinon) je organski spoj koji se nalazi u svim dijelovima biljaka iz obitelji Juglandaceae i poznato je da uzrokuje inhibiciju klijanja i rasta (Kocacë Aliskan i Terzi, 2001). Međutim, potrebna su dodatna, detaljnija istraživanja kako bi se potvrdio potencijal i opseg nakupljanja juglona u tlu pod nasadima oraha. Kako bi se dobile detaljnije informacije o učinku stabala na prinos kukuruza, izračunat je i prinos po usijanoj površini, tj. isključujući površinu koju zauzimaju stabla, ali još uvijek uzimajući u obzir smanjenu gustoću biljaka kukuruza. U ovom slučaju, prinos kukuruza po usijanoj površini bio je 96,61% od ostvarenog na kontrolnoj parceli bez drveća, što ukazuje na to da osim manje površine za uzgoj kukuruza i unatoč manjem broju biljaka koje su iznikle, stabla oraha nisu značajno utjecala na prinos kukuruza (Tablica 4).

Tablica 4. Prinos i komponente prinosa kukuruza

	Kontrola	Konsocijacija
Gustoća (sklop) [biljaka ha^{-1}]	67750 a	54000 b
Prinos zrna po usijanoj površini [kg ha^{-1}]	9448 a	9127 a
Prinos zrna po ukupnoj površini [kg ha^{-1}]	9448 a	6845 b
Masa 1000 zrna [g]	301.61 b	343.43 a
Žetveni indeks	0.43 a	0.52 a

Izvor: Žalac i sur., 2023. *srednje vrijednosti označene različitim slovima ukazuju na statistički značajne razlike između sustava ($P<0.05$; Tukey HSD test)

Ipak, smanjenje broja biljaka vjerojatno je kompenzirano povećanjem produktivnosti pojedinačnih biljaka (Ciampitti i Vyn, 2011; Hütsch i Schubert, 2017), tako da je kukuruz u konsocijaciji postigao veći žetveni indeks i značajno veću masu 1000 zrna od kukuruza na kontrolnoj parceli bez drveća (Tablica 4). Osim gustoće biljaka, za promatranje ovih razlika treba uzeti u obzir i čimbenike okoliša. Temperaturni pragovi za reproduktivni razvoj kukuruza znatno su niži od onih za vegetativni rast i često su premašeni za ljetne usjeve u našim krajevima. Akumulacija biomase i kapacitet za transport ugljika i hranivih tvari mogu biti znatno otežani pod takvim uvjetima, što dovodi do smanjenja broja i mase zrna (Shao i sur., 2021). Iako mikroklima unutar konsocijacijskog sustava može poboljšati remobilizaciju biomase prema zrnu (Li i sur., 2021), moguće je i da je kukuruz u konsocijaciji počeo ranije izdvajati asimilate u zrno nauštrb ukupne biomase zbog ograničene dostupnosti vode, odnosno konkurencije sa stablima oraha. Slična su opažanja ranije zabilježena za sirak (Wenzel i sur., 2000) i soju (Bunce, 1990). Ova teorija mogla bi objasniti utvrđene razlike između dva sustava u nadzemnoj biomasi biljke kukuruza tijekom vegetacije, masi 1000 zrna i žetvenom indeksu. Povećanje mase 1000 zrna od 12%

kod kukuruza u konsocijaciji u usporedbi s kukuruzom s kontrolne parcele slično je rezultatima dobivenim u istraživanju Temani i sur., (2021). Autori su utvrdili da je masa zrna graha u konsocijacijskom sustavu s maslinama povećana za 17%, a pšenice za 39%, u odnosu na referentne kontrolne parcele.

Prinos ploda oraha iznosio je ukupno 1777 kg ha^{-1} u konsocijacijskom sustavu i 2997 kg ha^{-1} u voćnjaku oraha, što je dalo relativni prinos oraha ($pLER_W$) od 0,59. Ovaj relativno nizak $pLER_W$ ne može se pripisati konkurenciji s kukuruzom i posljedica je nedefiniranih razlika između dva dijela voćnjaka. Naime, kao što je već spomenuto, promatrani voćnjak oduvijek je imao kontrastne prinose plodova između prvih i zadnjih pet redova stabala, odnosno, i prije početka usijavanja ratarskih kultura. Prvih pet redova uvijek je ostvarivalo znatno manje prinose od posljednjih pet, pa je povećanje ukupne produktivnosti ovog dijela voćnjaka bio razlog za usijavanje ratarskih kultura. Relativni prinos kukuruza ($pLER_M$) izračunat je na temelju prinosa po ukupnoj površini (uključujući i površinu koju zauzimaju stabla) i iznosio je 0,72. Zajedno, ove pLER vrijednosti dali su visok LER od 1,32, što znači da je konsocijacijski sustav bio 32% produktivniji po jedinici površine od pojedinačnog, tj zasebnog uzgoja oraha i kukuruza. I druga istraživanja, provođena pod različitim klimatskim uvjetima i dizajnom sustava, također su pokazala da konsocijacija kukuruza s drvećem može postići LER > 1 (Jama i sur., 1995; Bellow i sur., 2008; Selim i Shams, 2019; Karimuna i sur., 2022). Prethodno istraživanje ove disertacije temeljeno na simulaciji produktivnosti konsocijacijskih sustava pomoću Yield-SAFE sustava pokazalo je da, iako bi kukuruz u konsocijaciji mogao postići iznenađujuće visok prinos dok su stabla oraha mlada, do trenutka kada dosegnu 13. godinu, relativni prinos kukuruza ($pLER_M$) drastično pada i kreće se od 0,18 do 0,55, ovisno o scenariju gustoće stabla (Žalac i sur., 2021a). Međutim, do tada orah postiže punu zrelost za proizvodnju plodova i njegov relativni prinos ($pLER_W$) povećava ukupni LER. Ipak, zbog vremenske komplementarnosti u korištenju resursa između oraha i ratarskih usjeva, očekivano je da konsocijacijski sustavi s ozimim kulturama rezultiraju većim LER vrijednostima nego sustavi s jarim kulturama. U našim dosadašnjim istraživanjima, utvrdili smo da su najbolji ratarski usjevi sa stablima oraha u smislu produktivnosti po jedinici površine (LER) bili redom: ozimi ječam - 1,53 (Žalac i sur., 2022); višegodišnji ljulj - 1,44 (neobjavljeni podaci); kukuruz - 1,32; ozima pšenica - 1,18 (Ivezić i sur., 2019); heljda - 1,05 (Žalac i sur., 2022).

Pojedinačni sustav kukuruza, odnosno kontrolna parcela, usvojila je najviše vode, tj. imala je najveću evapotranspiraciju (WU) od tri promatrana sustava (Tablica 5). S obzirom na više temperature i nižu vlažnost, to je vjerojatno rezultat većeg udjela evaporacije vode iz tla nego što je slučaj u sustavima s drvećem (Jackson i Wallace, 1999; Lin, 2010; Siriri i sur., 2012). Najmanje vode potrošio je voćnjak oraha, što je vjerojatno rezultat kombinacije smanjene evaporacije i transpiracije samo stabala. Zbog većeg prinosa i odsutnosti konkurencije za vodu s drvećem, kukuruz na kontrolnoj parceli imao je veću produktivnost vode (WP) od kukuruza u konsocijaciji, iako ta razlika nije bila statistički značajna ($p>0,05$; Tukey HSD) (Tablica 5). Voćnjak oraha usvojio je manje vode nego konsocijacijski sustav, a s obzirom na mnogo veći prinos oraha u voćnjaku bez ratarskih usjeva, bio je i produktivniji po jedinici utrošene vode (WP). Međutim, konsocijacijski sustav ostvario je WER od 1,31, što znači da je kombinacija oraha i kukuruza bila 31% učinkovitija u korištenju vode od pojedinačnih sustava. WER vrijednost vrlo je slična dobivenoj LER vrijednosti, kao što je zabilježeno i u nekim drugim istraživanjima (Mao i sur., 2012; Bai i sur., 2016).

Tablica 5. Usvojena voda (WU[mm]), produktivnost vode (WP[kg ha^{-1} mm^{-1}]) i ukupna učinkovitost usvajanja vode za konsocijacijski sustav (WER)

Sustav	WU	WP	pWER	WER
Kukuruz - kontrola	272,75	40,3	-	-
Orah - voćnjak	244,75	12,2	-	-
Konsocijacijski sustav;	261,53			1,31
Kukuruz		30,4	0,76	
Orah		6,8	0,55	

Izvor: Žalac i sur., 2023.

Drveće pruža ekološke usluge smanjenjem gubitaka hranivih tvari putem sigurnosne mreže korijenja, podizanjem hranivih tvari iz dubokih slojeva tla, fiksacijom N_2 i promjenom morfoloških i kemijskih procesa u rizosferi (Isaac i Borden, 2019), što zatim može neizravno pogodovati učinkovitosti usvajanja hraniva usjeva u konsocijacijskim sustavima. Brojna istraživanja pokazala su da usjevi u konsocijaciji s drvećem mogu imati veći sadržaj hraniva u biomasi i/ili zrnu u usporedbi s usjevima uzgajanim bez prisutnosti drveća (Haggar i sur., 1993; Harawa i sur., 2006; Isaac i sur., 2007; Artru i sur., 2016; Pardon i sur., 2019). Ovakvi rezultati također su utvrđeni i u ranijem istraživanju na istoj lokaciji - ječam u konsocijaciji imao je značajno veći sadržaj N, P i K u zrnu od ječma na kontrolnoj parceli (Žalac i sur., 2021b). Međutim, kukuruz u ovom istraživanju ostvario je suprotne rezultate (Tablica 6).

Tablica 6. Sadržaj hraniva u zrnu i indeksi učinkovitosti; NP, PP, KP – produktivnost hraniva [kg ha^{-1}[kg hraniva u tlu ha^{-1}]$^{-1}$], NUE, PUE, KUE – učinkovitost usvajanja hraniva [kg ha^{-1} [kg usvojenog hraniva ha^{-1}]$^{-1}$], NRI, PRI, KRI – indeks mobilizacije hraniva [kg hraniva usvojenog u zrno ha^{-1}[kg hraniva u tlu ha^{-1}]$^{-1}$].

	Kukuruz - kontrola	**Kukuruz - konsocijacija**
N [%]	1,38 a	1,36 b
P [%]	0,25 a	0,25 a
K [%]	0,35 a	0,34 b
NP	43,21 a	54,68 a
PP	10,41 a	10,84 a
KP	7,90 a	6,97 a
NUE	25,33 a	29,01 a
PUE	160,75 a	176,91 a
KUE	47,44 b	57,98 a
NRI	0,88 a	0,70 a
PRI	0,03 a	0,03 a
KRI	0,03 a	0,02 a

Izvor: Žalac i sur., 2023. *srednje vrijednosti označene različitim slovima ukazuju na statistički značajne razlike između sustava ($P<0,05$; Tukey HSD test)

Gillespie (1989) tvrdi da se veća konkurencija između drveća i usjeva u konsocijacijskim sustavima javlja ponajviše za nitratni dušik i kalij. Sukladno tome su i ovi rezultati – kukuruz na kontrolnoj parceli imao je veći sadržaj dušika i kalija u zrnu (N% i K%) od kukuruza u konsocijaciji (Tablica 6). Iako je kukuruz u konsocijaciji imao veću učinkovitost usvajanja dušika, fosfora i kalija (NUE, PUE, KUE), što znači da je proizveo više suhe mase zrna po kg tih hraniva koje je akumulirao (Tablica 6), razlika je bila značajna samo za kalij. Rezultati ovog istraživanja usporedivi su s onima koje su utvrdili Ciampitti i Vyn (2012) i Ciampitti i sur. (2013) - učinkovitost usvajanja dušika i fosfora eksponencijalno se povećala kako je koncentracija tih hraniva u zrnu opadala. Veća učinkovitost usvajanja hraniva kukuruza u konsocijaciji utvrđena u ovom istraživanju mogla bi biti povezana sa smanjenom gustoćom biljaka, čime je smanjena i konkurencija između biljaka kukuruza. Nadalje, kukuruz u konsocijaciji ostvario je i nešto veći prinos zrna po raspoloživom dušiku i fosforu (NP i PP), što se može povezati s nižim sadržajem dušika i fosfora u tlu (Sainju i sur., 2021). Schmidt i sur. (2020) ispitivali su produktivnost hraniva u zrnu usjeva na tri različite vrste tla te su utvrdili da su ostvarene vrijednosti usporedive između usjeva u konsocijaciji i na zasebnim parcelama, zbog sličnih prinosa i dostupnosti hraniva u tlu. Slično rezultatima ovog istraživanja, nisu uočili prednosti u produktivnost kalija (KP), ali su utvrdili veću produktivnost dušika (NP) za usjeve u konsocijaciji na glejnom kambisolu. Indeksi mobilizacije hraniva (NRI, PRI, KRI) nisu pokazali značajnu razliku za kukuruz na kontrolnoj parceli i u konsocijaciji, što ukazuje da na sposobnost kukuruza da mobilizira hraniva u zrno nije utjecala potencijalna konkurencija sa stablima oraha.

6. ZAKLJUČCI

- Korištenjem simulacijskih modela Yield-SAFE i Farm-SAFE predviđeno je da bi, osim visokih prinosa kukuruza u prvih nekoliko godina, prinosi ratarskih usjeva u konsocijaciji s orahom bili manji od onih na kontrolnoj parceli bez drveća, te da bi i usjevi mogli ograničiti produktivnost stabala oraha. Ipak, zbroj relativnih prinosa u konsocijaciji dao je LER > 1, što znači da bi ovakav sustav bio produktivniji od pojedinačnih uzgoja oraha i usjeva, čak i nakon 20 godina. Usijavanje ratarskih usjeva tijekom prvih 6 godina od sadnje oraha pružilo je i financijsku dobit, omogućivši nadoknadu visokih troškova podizanja voćnjaka osiguravanjem dodatnih prihoda. Ovakav scenarij pokazao se kao najisplativiji tijekom simuliranog razdoblja, međutim, nastavak usijavanja ratarskih kultura tijekom punih 20 godina nije pokazao nikakvu prednost u odnosu na uzgoj samo oraha. Analiza je također pokazala da je gustoća od 170 stabala ha^{-1} rezultirala najvećim neto maržama za svaku od 20 simuliranih godina.
- Značajan utjecaj na mikroklimu zabilježen je u starijem voćnjaku, što je rezultat većih stabala oraha i užih sadnih razmaka. Konsocijacijski sustavi na ovom lokalitetu imali su smanjenu evapotranspiraciju u odnosu na kontrolne parcele usjeva bez drveća, za sve tri promatrane godine. Mjerenja dnevne temperature i relativne vlažnosti zraka pokazala su ublažavanje ekstremnih uvjeta unutar redova kukuruza u konsocijaciji, a ovaj efekt bio je najznačajnije izražen tijekom vrućih i suhih ljetnih mjeseci.
- Bez obzira na smanjenje prinosa ratarskih usjeva u konsocijaciji s orahom u odnosu na kontrolu, ovi sustavi su ostvarili veću produktivnost po jedinici površine. LER vrijednosti iznosile su redom 1,05, 1,32 i 1,53 za sustave s heljdom, kukuruzom i ječmom, redom.
- Zbog kompeticije sa stablima oraha, produktivnost usjeva po jedinici usvojene vode bila je manja u konsocijaciji nego na kontrolnim parcelama. Ipak, uzevši u obzir cijeli sustav, utvrđena je i prednost u učinkovitosti usvajanja vode, te su konsocijacijski sustavi ostvarili WER vrijednosti od 1,12, 1,31 i 1,83 za kombinacije s heljdom, kukuruzom i ječmom, redom.
- Iako su utvrđene značajne pozitivne mikroklimatske promjene u konsocijaciji s orahom, utvrđen je negativan utjecaj stabala oraha na klijavost kukuruza, što je

utjecalo i na značajno niži prinos po ukupnoj površini u odnosu na kontrolu. Ipak, smanjenje broja biljaka kompenzirano je povećanjem produktivnosti pojedinačnih biljaka pa je kukuruz u konsocijaciji postigao veći žetveni indeks i značajno veću masu 1000 zrna. Nisu pronađene značajne razlike između dva sustava kukuruza u produktivnosti po jedinici dostupnog hraniva u tlu, kao ni u učinkovitosti mobilizacije dostupnih hraniva u zrno. Ipak, kukuruz u konsocijaciji proizveo je veći prinos zrna po jedinici usvojenog dušika i kalija.

- Usijavanje ratarskih kultura u voćnjake oraha dobra je mjera prelaska s ratarske na voćarsku proizvodnju ili mjera intenziviranja poljoprivredne proizvodnje, međutim, vrlo je bitan odabir vrsta i dizajn sustava kako bi ovakva praksa bila i ekološki i ekonomski održiva.

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Naslova rada: Modelling the yield and profitability of intercropped walnut systems in Croatia

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Modelling the yield and profitability of intercropped walnut systems in Croatia

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Abstract In Croatia, farmers are showing increasing interest in establishing walnut orchards for nut production on arable land due to higher anticipated net margins. One way to address the lack of profitability in the initial years when nut yields are low may be to plant arable intercrops. The anticipated impacts of this practice were assessed using a biophysical simulation model (Yield-SAFE) to determine the growth and yield of crops and trees in arable, orchard, and silvoarable systems, and an economic farm model (Farm-SAFE) was used to assess their profitability. The walnut orchard and the intercropped orchard systems were simulated assuming tree densities of 170, 135, and 100 trees ha^{-1}, to determine the profitability and break-even date of the systems. The biophysical simulation predicted a decline in arable intercrop yields over time in all tree density scenarios. However, analysis of productivity of intercropped systems showed that intercropping was more productive than separate arable and walnut production for all tree density scenarios. From financial aspect, the return from intercropping helped to offset some of the initial orchard establishment costs and the arable intercrop remained profitable until the sixth year after tree planting. The modelling predicted that a system with 170 trees ha^{-1} that included intercropping for the first 6 years provided the greatest cumulative net margin after 20 years. The financial benefit of intercropping over the first 6 years opposed to monoculture walnut fruit production appeared to be consistent across the three tree densities studied. These results suggest that silvoarable agroforestry is profitable approach to establishing walnut orchards.

Keywords Bio-economic model · Silvoarable agroforestry · Intercropping · Walnut · Orchard

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Introduction

Agroforestry, the combined production of woody perennials with crops (silvoarable) or livestock (silvopastoral), is a significant land use in Europe covering 15.4 million ha (den Herder et al. 2017), with the largest areas occurring in southern Europe. Although most of this area comprises silvopastoral systems, about 222,000 ha of agroforestry comprises the intercropping of arable crops with high value trees such as olives, nuts and fruit trees (den Herder et al.

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2017; Pantera et al. 2018). The addition of trees to arable systems offer a range of positive ecological effects such increased carbon sequestration (Palma et al. 2007b; Cong et al. 2015; Cardinael et al. 2017), enhanced biodiversity (Tsonkova et al. 2012; Torralba et al. 2016), reductions in nutrient loss and pesticide runoff (Pardon et al. 2017), and improvements of water availability and formation of positive microclimatic conditions (Quinkenstein et al. 2009).

The ecological benefits of tree planting on arable land, has encouraged the European Union to provide financial support for new agroforestry systems. Between 2007 and 2013, the EU Rural Development Programmes (RDPs) included Regulation 1698/2005 (The Council of the European Union 2005) which promoted the first establishment of new agroforestry systems on arable lands. However, a study in the UK, indicated that for most farmers, silvoarable systems need to show a financial advantage before they decide to switch from arable to silvoarable production (Graves et al. 2017). The exact financial and ecological benefits of a particular system, relative to arable cropping, will depend on a range of factors such as the climate, tree density, and choice of tree and crop species (Graves et al. 2007). One way to determine the anticipated impact of intercropping in a specific situation is to use a simulation model to predict the most important climate, soil, tree and crop effects and interactions in biophysical and financial terms. The biophysical Yield-SAFE model (van der Werf et al. 2007) and the bio-economic Farm-SAFE agroforestry model (Graves et al. 2011) were developed to inform European farmers and policy-makers on the potential of silvoarable agroforestry and to help reduce the uncertainties as part of the European Union sponsored SAFE project between 2001 and 2005. Both these models were further developed during the EU sponsored AGFORWARD project between 2014 and 2017 (Burgess and Rosati 2018). The developments include the creation of a climate database called CliPick (Palma 2017), and the integration of improved soil carbon algorithms within the Yield-SAFE model (Palma et al. 2018).

Previous research on the viability of silvoarable agroforestry in Europe has been largely based on the use of trees for timber production (Palma et al. 2007a; van der Werf et al. 2007; Graves et al. 2007, 2010). By contrast, there have been few publications on the biophysical and financial outputs of systems involving nut or fruit trees.

Walnut trees (*Juglans* species) produce nuts of high nutritional value which are rich in proteins, minerals and vitamins, and the oils are perceived to have health benefits (Ozkan and Koyuncu 2005). Walnuts are produced under a range of climate and soil conditions, but yields are reported to be highest in warm and temperate regions. Ahmad et al. (2018) report that optimal growing conditions included about 760–800 mm of well-distributed annual precipitation, deep, friable and permeable loam/silt loam or clay loam soils with a pH of 5.5–6.5, well supplemented with lime, and rich in humus. Walnut is sensitive to late spring and early autumn frosts as freezing temperatures kill the growing point of walnut trees and severely affects production. The recommended tree density depends on the climate, soil conditions and cultivars (Ahmad et al. 2018). In Croatia, walnuts are usually planted from a classic distance of 10 × 10 m (100 trees ha^{-1}) up to 5 × 5 (400 trees ha^{-1}) for intensive plantations with smaller, lateral varieties. Although grafted walnuts can bear their first fruits as early as the 3rd or 4th year, they do not give a significant yield before the 8th year. There is no published reference on walnut yields in Croatia, but according to the articles from Croatian Ministry of Agriculture advisory website, in full maturity, a well-maintained plantation can yield 3.5–4 tons per hectare of walnuts in shell, although this again depends on cultivar and appropriate pruning of the canopy (Orah - značajna voćna vrsta 2007). On the other hand, personal communication with expert organizations involved in walnut production in Croatia indicated that farmers are mostly cultivating terminal cultivars and that such grafted walnuts usually produce around 2 t ha^{-1} of nuts in shell by year 10–15 (NGO "Pupoljak", personal communication). The recommended practice is to initially shorten the seedlings in the spring at a height of 1.5–2 m, from where new apical and lateral buds will appear. Out of those lateral buds, three are typically selected and left to grow to form the future primary branches of a vase-shaped canopy. In the second and third year the pruning is directed to the formation of the trunk and canopy (Orah 2009). Walnut tree growth and production is typically enhanced by nitrogen application, with a recommended application of 100 g N per tree in the first year, and 200 and 400 g N per tree in year two and three. Also, after planting, application of 20–30 kg of manure is recommended around each seedling (Japundžić 2017).

Recently in Croatia, spurred by government subsidies, interest in raising walnut orchards has been growing. We observed a constant increase in the total area under walnut orchards since 2014, which was one of motives for our research. According to the latest data, it amounts 5554 ha and it is the second-largest area in fruit production, right after olive orchards (Croatian Bureau of Statistics 2018).

This study examines the predicted yield and financial impacts of establishing a semi-intensive intercropped walnut nut production systems in Croatia in Europe, as a transitional option from arable farming to fruit growing. The key questions are how does tree density affect the profitability of the arable crops and walnuts in three tree density scenarios, and how this compares with a pure arable system and pure orchard systems at the same density?

Material and methods

Systems description

Arable, walnut orchard and intercropped walnut orchard systems were simulated for 20 years period to explore its agronomic and financial returns. For arable component in the arable system and intercropped orchards, rotation of grain maize, barley and rapeseed was chosen, as common crop rotation in Croatia. Walnut input parameters were chosen considering cultivar with intermediary fructification. For walnut orchards and intercropped walnut orchards three tree density scenarios were simulated; 170, 135 and 100 trees ha^{-1} planted in a rectangular layout assuming distances between tree rows of 8, 10 and 12 m, respectively. Accordingly, crop alley widths in intercropped systems were selected to be 6, 8 and 10 m, leaving 1 m distance from trees on each side and giving the crop area of 75%, 80% and 83%, respectively. In the walnut-only system, a grass cover was considered for system simulation.

Site description and climate

Đakovo in eastern Croatia (Fig. 1), an area with a continental climate of warm summers and cold winters, was chosen as the case study site for examining the agronomic and financial effects of different agroforestry designs. The altitude of the site is 111 m, the soil type is loam and the effective soil depth is 1500 mm. The mean air temperature is typically − 2 to 0 °C in January, and 18–22 °C in July. The mean annual rainfall is 600–1000 mm and relatively evenly distributed throughout the year. In order to run the agroforestry simulation model, representative predicted daily weather data for the site in eastern Croatia for the period 2019–2039 was derived from CliPick (Palma 2017). Clipick weather data was validated by comparing its predicted data with the observed data from the local meteorological station.

Prediction of arable crop and walnut yields using Yield-SAFE

The prediction of the arable crop yields in an agroforestry system with the Yield-SAFE model firstly requires the calibration of the model for known arable crop yields in the absence of trees. Parameters for soil, tree and crop are shown in the supplementary material. The three parameters that were used for calibration were the amount of water transpired by the crop and tree, the crop harvest index and the management parameter—day of sowing. The parameterization and calibration of Yield-SAFE is explained in more details in van der Werf et al. (2007) and Graves et al. (2010). The assumed rotation for the arable system was a 3 year rotation of grain maize, barley and rapeseed. The typical planting months for these crops in Eastern Croatia are April for grain maize, early October for barley and late August for rapeseed. For calibration purposes, mean crop yields for these crops for the period 2013–2017 were derived from the Croatian Statistical Yearbook (Croatian Bureau of Statistics 2018), considering rotation starting with grain maize in 2013 and then compared with calculated rotation yields for the same years. After calibration, simulations were run for the period 2019–2039.

There is no published reference on walnut yields in Croatia. Personal communication with expert organizations involved in walnut production in Croatia and farmers cultivating mostly terminal cultivars indicated that grafted walnuts can start to yield nuts in year 4 and a typical yield of nuts with shells is around 2.5 t ha^{-1} by year 15. Assuming 100–175 trees ha^{-1}, this equate

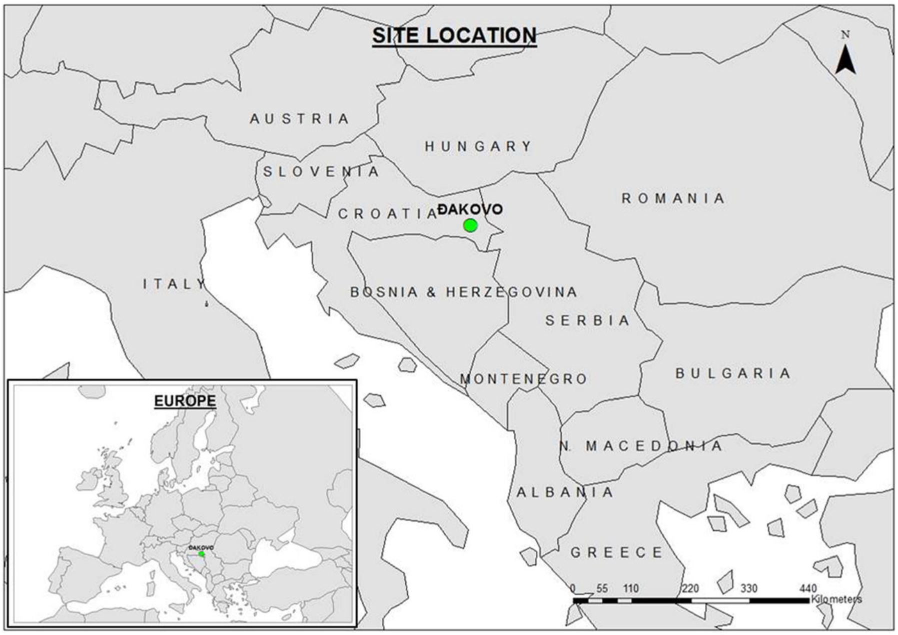

Fig. 1 Site location

to 15–25 kg per tree (NGO "Pupoljak", personal communication).

Productivity analysis

Arable crop yields in the intercropped orchards were simulated under tree densities of 170, 135 and 100 trees ha^{-1} with proportional crop areas of 75%, 80%, and 83% respectively. Annual walnut fruit production was modelled for these tree densities for pure walnut and intercropped walnut orchards, and expressed in kg ha^{-1}. From the crop and fruit yields, annual land equivalent ratios (LER) were estimated for each tree density scenarios. The land equivalent ratio is defined as the ratio of the area under monoculture production to the area under intercropping needed to give equal yields at the same management level (Ong and Kho 2015). It is calculated as the ratio of tree silvoarable nut yield to the tree monoculture nut yield plus the ratio of crop silvoarable yield to the crop monoculture yield as shown in Eq. 1:

$$\mathrm{LER} = \frac{\textit{Tree silvoarable yield}}{\textit{Tree monoculture yield}} + \frac{\textit{Crop silvoarable yield}}{\textit{Crop monoculture yield}} \tag{1}$$

When LER ≤ 1, there is no agronomic advantage of intercropping over sole cropping, but when LER is > 1, production in the intercropped system is higher than in the separate sole crops. In our model the same number of trees were considered for tree silvoarable yields as for tree monoculture yield in order to investigate the productivity and profitability of the same walnut densities with and without arable cropping.

Financial analysis using Farm-SAFE

A financial model of the arable, walnut-only, and the intercropping systems was developed using the spreadsheet-based bio-economic model called Farm-SAFE (Graves et al. 2011). Production costs (Tables 1 and 2) were obtained from interviews with farmers and complemented with cost calculations from the Croatian Agricultural and Forestry Advisory Service (Croatian Agricultural and Forestry Advisory Service 2018). The values of arable crops were from Croatian market prices (Table 2). The value of a green walnut picked in early summer is about 0.50 € kg^{-1}. By contrast a walnut kernel sold without a shell at the end of summer can reach prices of up to 10 € kg^{-1}. However, the mean price for kernels in their shell is

Table 1 The assumed costs of walnut nut production

Activity	Cost	Value
Establishment	Labour for ground preparation (€ ha^{-1})	280
	Labour for marking out (€ ha^{-1})	135
	Labour for weeding (€ ha^{-1})	6
	Labour for planting (€ per tree)	2
	Cost of plant (€ per tree)	16
	Cost of individual tree protection (sprays + labour) (€ per tree)	2.75
	Fertiliser application (fertilizer + labour) (€ per tree)	0.5
	Cost of harvest (€ t^{-1})	540
Maintenance	Labour for weeding (€ per tree)	0.15
	Labour for pruning and removal of prunings (€ per tree)	0.08

Table 2 The assumed revenue and costs associated with arable crop production

	Component	Rapeseed	Barley	Maize
Revenue	Area payment (€ ha^{-1})	245	245	245
	Grain or oilseed (€ t^{-1})	325	140	135
	Straw (€ t^{-1})	na	25	31
Costs	Seed price (€ kg^{-1})	15	0.4	8
	Seed rate (kg ha^{-1})	5	200	20
	Cost of N fertiliser (€ kg^{-1} N)	1.9	1.6	1.87
	N fertiliser rate (kg N ha^{-1})	105	95	155
	Cost of P fertiliser (€ kg^{-1} P)	1.3	0.95	1.54
	P fertiliser rate (kg P ha^{-1})	150	100	130
	Cost of K fertiliser (€ kg^{-1} K)	0.93	0.83	1
	K fertiliser rate (kg K ha^{-1})	215	120	250
	Spray price (€ per application)	80	120	103
	Spray rate (app ha^{-1})	1	1	1
	Machinery (€ ha^{-1})	200	240	250

na not applicable

1.62 € kg^{-1}, which is the price included in our calculations. It was assumed that the walnut trees were solely grown for nut production. The timber value of the trees was assumed to be zero as the trees grown for fruit in semi-intensive orchards do not reach large biomass or height and shaping trees to have higher trunks compromises the fruit yield. Also, the felling cost is similar to the revenue derived from selling the wood for firewood.

The profitability of arable system, walnut orchard and intercropped walnut orchard was assessed deriving annual net margins per hectare for each system and each scenario. The annual net margin values for production with by-products (i.e. the straw from maize and barley) were determined for the arable system. The net margin was calculated as revenues from harvested products and grants (R_t) minus variable (V_t) and assignable fixed costs (A_t) of production which are specified for each year (t) over a time horizon of T (years) and expressed as a net present values (NPV) using a discount rate (i) to determine the present value of future income flows (Eq. 2);

$$NPV = \sum_{t=0}^{t=T} \frac{(R_t - V_t - A_t)}{(1+i)^t} \tag{2}$$

The discount rate of 4% was chosen as reported by European Commission 2014 and used by Graves et al. (2007) and García de Jalón et al. (2018). Cumulative net margins over the assumed rotation were calculated by adding up annual NPV values and payback periods were determined for each system and scenario.

Results

Monocrop arable yields

Actual mean yields of grain maize in Croatia in 2013 and 2016 were 6.5 and 8.5 t ha^{-1}; mean yields of barley were 3.8 t ha^{-1} in 2014 and 4.8 t ha^{-1} in 2017, and the mean rapeseed yield was 2.6 t ha^{-1} in 2015. The modelled yields of grain maize (8.5 and 9.7 t ha^{-1}), barley (4.8 and 4.1 t ha^{-1}) and rapeseed (2.8 t ha^{-1}) were broadly similar to the observed yields (Fig. 2) with a strong correlation of 0.954 ($p < 0.05$).

Walnut fruit production in intercropped orchard

The parameterised Yield-SAFE model predicted annual walnut yields (in shell basis) to increase to about 20 kg per tree by year 20. By year 20, the fruit yields in the intercropped and walnut-only system were broadly similar, but the yield per hectare was dependent on the tree density, ranging from 2038 kg ha^{-1} with 100 trees ha^{-1} to 3679 kg ha^{-1} at a tree density of 170 trees ha^{-1} (Fig. 3).

The model predicted that the arable crops would substantially reduce walnut yields in the initial 10 years (Table 3). This effect of crops on trees could be due to underground competition for water since crops can alter and limit water availability to the roots of young trees. Water limitation reduces the growth of trees, which can then delay and reduce fruit yield. However, the predicted walnut yields in intercropped orchard exceeded walnut yields in pure walnut orchard after year 12 for density of 100 trees ha^{-1} and year 13 and 14 for densities of 135 and 170 trees ha^{-1}, respectively (Table 3).

Modelling crop yields in intercropped orchards

With the calibrated crop and walnut parameters, the model was used to predict the effect of the three tree densities on the intercrops yield per total area. Up to the seventh year after planting, the relative crop yields within the intercropping systems were between 82 and 114% of those in the monoculture system at each of the three tree densities (Fig. 4). However, after year 7, when trees are well developed and dominant in both aboveground and belowground competition, the predicted relative crop yields were below 70% (Fig. 4) with the highest intercropping yields predicted at 100 trees ha^{-1} and the lowest at 170 trees ha^{-1}. Among the crop species, grain maize gave the highest predicted relative yields e.g. 1.14 in the first year, and barley resulted in the lowest relative yields. These results are not expected as spring crops, such as grain maize usually result in lower yields than winter crops in intercropped systems. However, it is not impossible for spring crops to achieve such high yields in the first years of intercropping while the trees do not have a large canopy and have no significant competition for

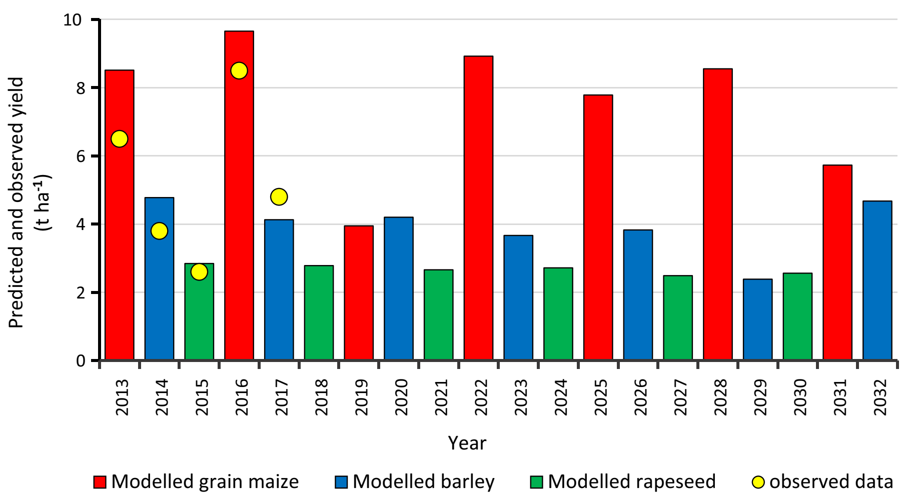

Fig. 2 Modelled (2013–2032) and measured (2013–2017) mean annual crop yields in a grain maize (2013 and 2016), barley (2014 and 2017) and rapeseed (2015) rotation

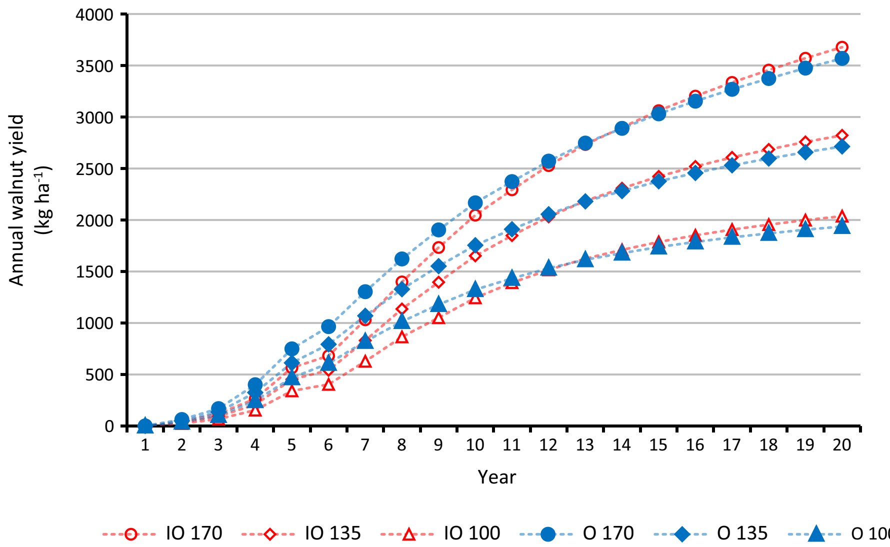

Fig. 3 Modelled walnut fruit production for three tree-densities during the first 20 years expressed in kilograms per hectare: *IO* intercropped orchard, *O* orchard (170, 135, 100 trees ha^{-1})

Table 3 Modelled relative walnut yield per hectare of an orchard including intercropping, relative to a non-intercropped orchard, at three densities

Year	Crop	Tree density		
		170 trees ha^{-1}	135 trees ha^{-1}	100 trees ha^{-1}
1	Maize	0.50	0.50	1.00
2	Barley	0.67	0.67	0.66
3	Oilseed	0.72	0.69	0.67
4	Maize	0.66	0.64	0.63
5	Barley	0.75	0.74	0.73
6	Oilseed	0.71	0.68	0.67
7	Maize	0.79	0.78	0.77
8	Barley	0.86	0.86	0.85
9	Oilseed	0.91	0.90	0.89
10	Maize	0.94	0.94	0.94
11	Barley	0.97	0.97	0.97
12	Oilseed	0.98	0.99	0.99
13	Maize	0.99	1.00	1.01
14	Barley	1.00	1.01	1.02
15	Oilseed	1.01	1.02	1.03
16	Maize	1.02	1.03	1.04
17	Barley	1.02	1.03	1.04
18	Oilseed	1.02	1.03	1.05
19	Maize	1.03	1.04	1.05
20	Barley	1.03	1.04	1.05

sunlight. As for grain maize, it has deep roots that in the first years of intercropping, while the trees have not yet fully developed their own, have room to spread out and absorb enough nutrients and water.

Land equivalent ratio (LER)

Using the model it was possible to derive the annual LER for the three density scenarios. The intercropped walnut orchard was assumed to have the same number

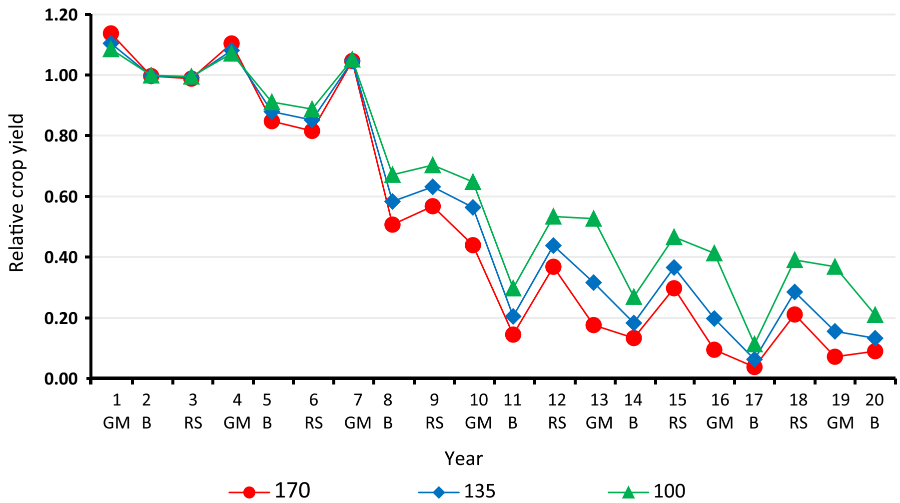

Fig. 4 Predicted relative crop yields for the walnut intercrops at three densities: *GM* grain maize, *B* barley, *RS* Rapeseed (170, 135, 100 trees ha^{-1}) calculated per total area

of trees as the control walnut-only orchard. Although the model predicted walnut yields in both the first (1–2 kg ha^{-1}) and second year (25–64 kg ha^{-1}), in reality, the walnut does not yield at least the first 2 years. For this reason, we investigated and presented LER starting from year 3. So, in the third year, the predicted LER for the three tree densitities were; 1.71 in the 170 trees ha^{-1} system, 1.68 in the 135 trees ha^{-1} system and 1.66 in the 100 trees ha^{-1} system. As relative walnut yield was increasing with time (Table 3), crop relative yield decreased significantly (Fig. 4.) which showed an effect on annual LER values. So by year 20, the LER had declined to 1.38 at 170 trees ha^{-1}, 1.43 at 135 trees ha^{-1}, and 1.53 at 100 trees ha^{-1}.

Net margins of crop production

The net margin from the crop system includes both the revenue of the main crop and the by-product. Including the revenue from the by-product increases the net margin of the maize and the barley crop; there was no by-product with the rapeseed crop. The highest net margin in the arable system was achieved from the maize crop in year 1 (353 € ha^{-1}) and year 4 (476 € ha^{-1}). The least profitable crop was barley. The net margin from the arable component of all silvoarable systems showed substantial losses after year 6, meaning it was no longer profitable to intercrop in walnut orchard with any of the three tree densities.

Cumulative net margins

The predicted cumulative net margins are discounted future values at a discount rate of 4%. For the arable system in year 20, the net present value was 2573 € ha^{-1} (Fig. 5). The establishment costs, which were between 1600 and 3500 € ha^{-1}, in the walnut-only and walnut intercropped systems, meant that the net margin was negative in the initial years (Fig. 5). Due to more plant material needed, as well as labor, the establishment costs were greater for the 170 tree ha^{-1} system than the 100 tree ha^{-1} system.

The intercropped system of 100 trees ha^{-1} was predicted to break-even in year 4 and intercropped system of 135 and 170 trees ha^{-1} in year 5. By contrast, the walnut-only systems were predicted to break-even 1 year later; orchard with 100 trees ha^{-1} in year 5, and orchards with 135 or 175 trees ha^{-1} in year 6.

After 6 years, the continued cropping of an intercrop started to substantially reduce the cumulative net margin of the intercropped systems, to the extent that the walnut-only systems started to become more profitable. Because arable cropping below the trees was no longer profitable after year 6, the net margin of the silvoarable system can be improved by stopping intercropping in year 7. The results showed that stopping intercropping after year 6 and maintaining an orchard for the remaining 14 years provided a greater cumulative net margin than intercropping for full 20 years and the sole walnut orchard systems at equivalent tree densities. The greatest NPV

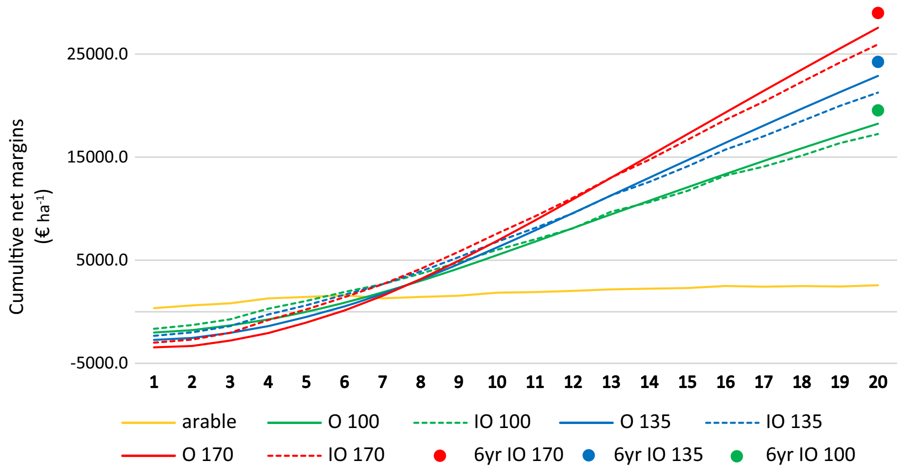

Fig. 5 Discounted (4%) cumulative net margins of the arable system, and the walnut-only and walnut-intercropping systems with a tree density of 170 trees ha^{-1} (crop area in the intercropped orchard: 0.75), 135 trees ha^{-1} (crop area in the intercropped orchard: 0.80), 100 trees ha^{-1} (crop area in the intercropped orchard: 0.83), *O* orchard, *IO* intercropped orchard (170, 135, 100 trees ha^{-1}) over 20 years and intercropped systems stopped when no longer profitable—after 6 years

(28,986 € ha^{-1}) was obtained for the 6-years intercroped orchard at 170 trees ha^{-1} (Table 4).

Discussion

To the best of our knowledge this is the first attempt to use bio-economic models to compare the yields and net margins associated with nut production in Croatia from intercropped and sole orchard systems at equivalent tree densities, as well as the first application of Farm-SAFE model where walnut fruit production is the main objective of establishing intercropped system with walnut. The results are discussed in terms of the biophysical modelling of tree and crop yields and the financial implications, which can serve as an insight into the possibilities of establishing silvoarable practice for Croatian farmers, as well as farmers in Eastern Europe area with the same climatic and economic conditions.

The Yield-SAFE model predicted the highest walnut yields per hectare for walnut-only and intercropped system with a tree density of 170 rather than those with 135 or 100 trees ha^{-1} (Fig. 3). However, the increasing competition between the trees for light and water meant that individual tree fruit production (kg tree^{-1}) was greatest in orchards at 100 trees ha^{-1}. Similar effects at high tree densities, resulting in greater light and water competition, and hence lower timber volumes per tree have also been reported by Graves et al. (2010). The simulation also showed that the arable crops would initially reduce annual nut production (Table 3), most likely by limiting available water for tree roots and therefore limiting its growth,

Table 4 Discounted (4%) cumulative net margins of the walnut orchard, the intercropped orchard, and the orchard intercropped for the first 6 years, calculated over 20 years (€ ha^{-1})

Tree density	Net present value (€ ha^{-1})		
	Walnut orchard	Intercropped orchard for 20 years	Intercropped orchard until crop component is profitable
170 trees ha^{-1}	27,551	25,936	28,986
135 trees ha^{-1}	22,880	21,263	24,240
100 trees ha^{-1}	18,243	17,244	19,539

as seen in research by Burgess et al. (1996). However as the trees increased in size and became dominant species in the competition for resources, the model predicted that the annual nut yields in intercropped orchards would no longer be affected by crops and would even exceed nut yields in walnut-only systems, however this difference was not statistically significant.

The Yield-SAFE model predicted high relative crop yields in early years of intercropped systems for maize (1.05–1.14 in year 1, 4 and 7). Although unexpected, such yields are not impossible and have been reported earlier by other authors (Burgess et al. 2004; Seserman et al. 2019). In traditional Dehesa systems in Spain and Portugal vicinity of trees showed a beneficial effect on crop growth (Moreno 2008; Gea-Izquierdo et al. 2009). Since maize is a spring crop, summer droughts can result with decrease in maize yields. Microclimatic conditions in orchards, in terms of increased humidity compared to an open field, might have the beneficial effect on maize yields in early years while enough light was still available for the crop. Besides these high relative maize yields, the model predicted a steady decline in relative arable crop yields as the walnut trees grew—they dropped below 0.7 after year 7 (Fig. 4). Within the model, this decline occurs due to increasing competition for water and light. Similarly, Newman (2006) in trials from Buckinghamshire and Essex reported that arable yields within a poplar agroforestry system could be maintained for 10 years until tree competition became too severe. The simulations demonstrated that the greatest decline in crop yields occurred at the greatest tree density of 170 trees ha^{-1}. Similarly, results from previous studies showed a greater decrease in relative crop yields in silvoarable systems at 113 trees ha^{-1} than at 50 trees ha^{-1} (Graves et al. 2007).

Overall, the calculated LER of the intercropped systems over the full 20 years of intercropping the LER was between 1.38 for 170 trees ha^{-1} and 1.53 for 100 trees ha^{-1}. These full-rotation values are similar to values of between 1.00 and 1.40 reported from modelling studies for timber trees in other European countries undertaken by Graves et al. (2007).

The financial analysis demonstrated that the arable system produced a positive and relatively consistent cashflow over 20 years (Fig. 5), whereas the agroforestry and the tree-only system started with substantial losses, which were only reversed as the walnut system started to produce walnuts. The initial costs of orchard establishment were 1600–3500 € ha^{-1} depending on the tree density. However, over a period of 20 years, the predicted returns from the walnut systems were significantly greater than arable cropping. This coincides with the current interest in establishing walnut orchards in Croatia. It should be noted that the above financial analysis ignores the possibility of catastrophic or partial damage to the walnut system through fire, vandalism, or pest damage. Incorporating such effects into a financial analysis is difficult, but it should be part of the consideration before any investment decision.

During the first 6 years of the walnut plantation, intercropping was predicted to increase the net margin. However, continued cropping beyond this period resulted in financial losses as crops could not reach satisfactory yield and income in silvoarable systems. In practice, as soon as crop production in the intercropped system becomes unprofitable, a farmer would stop intercropping. With this scenario of intercropping stopped in year 7, the system resulted in a greater net margin over 20 years than the walnut-only system (Table 4), which showed that this silvoarable practice is a profitable option for transitioning from arable farming to walnut nut production. However, in the most intensive system, with a density of 170 trees ha^{-1}, which was the most profitable out of all densities, the difference in the net margin between the walnut-only system (27,551 € ha^{-1}) and system with intercropping for the first 6 years (28,986 € ha^{-1}) is only €1435 ha^{-1}. It remains arguable whether this financial benefit is sufficient for a farmer to practice intercropping, particularly if the intercropping results in additional administrative and managerial work. This analysis has focused solely on the agronomic and financial analysis of the systems. In practice, growing trees rather than arable crops can provide ecological benefits such as increased carbon storage, reduced water pollution, and enhanced biodiversity than can be ascribed financial values (García de Jalón et al. 2018). This can greatly increase the social value of tree-based systems.

Conclusion

The use of the Yield-SAFE and Farm-SAFE agroforestry simulation models highlights some of the opportunities and challenges associated with the possibility of intercropping in the newly established walnut orchards. Here, it highlighted that beyond the high grain maize yields in initial years, the yield of an intercropped arable crop would be less than that in a control arable field, and that the crop could also restrict the productivity of the walnut trees. However, it also showed that intercropping systems could have a very high land equivalent ratio in the initial years of planting and that even after 20 years of intercropping, the predicted LER was above 1. These LERs indicate that growing walnut trees and crops in the intercropped system is more productive than growing them separately. Intercropping for the first 6 years provided financial benefit, allowing the offset of high orchard establishment costs by providing the additional revenue from the crops. However, intercropping for full 20 years showed no advantage over cultivating pure walnut orchard. The analysis also indicated that a density of 170 rather than 100 trees ha^{-1} resulted in the highest net margins for each year of a 20-year rotation.

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Land and Water Productivity in Intercropped Systems of Walnut—Buckwheat and Walnut–Barley: A Case Study

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Abstract: Intercropping arable crops in orchards is a sustainable land use for intensifying agricultural production, under the condition of plants' complementarity in sharing resources. This study investigated the aspects of water use and yields in intercropped systems of walnut and crops. To assess possible temporal complementarity between crops and trees, a summer crop—buckwheat—and a winter crop—barley—were intercropped in walnut orchards. The land and water productivity were studied under two designs: in an older, denser orchard and a younger one, with wider tree spacing. The results showed a reduction in yields and water productivity (WP) of intercrops due to the competition with walnut trees, with the exception of buckwheat in the younger orchard, where this summer crop surprisingly achieved the highest yield and WP. Nevertheless, in the system with mature fruiting trees, intercropping with winter barley was 53% more productive per unit of land and 83% more water-productive than growing walnut and barley separately but also 48% more land-productive and 70% more water-productive than the walnut–buckwheat system. Our results indicate positive effects of trees on microclimates but also emphasize the importance of species selection and systems design on the overall productivity of intercropped systems.

Keywords: agroforestry; intercropped orchard; walnut; water productivity; water equivalent ratio; land equivalent ratio

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1. Introduction

In recent decades, it has become apparent that climate change could be a significant threat to agricultural production, especially in semi-arid and arid areas suffering from drought. The climate assessment in Croatia, conducted by Perčec Tadić et al. [1], shows that the prevailing precipitation deficit occurs during the warm season. Regarding the Pannonian region, where most of the arable land is, a precipitation deficit occurs on a monthly basis. It is most pronounced in the region's eastern part from April to September. The authors classified this area as moderately vulnerable to drought, with its generally not irrigated arable land being the most sensitive.

Agroforestry systems, characterized by the addition of trees to agroecosystems, have a great potential for climate change mitigation, as well as providing better adaptation of food production systems to the changing climate conditions [2]. The addition of trees on arable land modifies the microclimate of the cultivated area, primarily by influencing radiation flux, reducing air temperature and wind strength, which increases relative air humidity. These changes can reduce evapotranspiration and improve the system's water utilization. Regardless of the positive effects of trees on microclimate conditions, there is always uncertainty about the productivity and profitability of understory crops, as their yields depend on many factors. Primarily, crop yields are determined by climate and soil properties. However, tree species, age, density, and management significantly affect the amount of shade and competition for belowground resources, so different species combinations in these systems give very different outcomes [3]. Although the reduction in crop yields in an intercropped system with trees is expected and recorded, studies showed that with a proper system design and species selection, competition could be reduced to the level where the crop in the intercropped system gives the same yields as a crop in monoculture [4], if not higher [5,6]. Despite low relative crop yields, these systems often have higher productivity [7–9], which may be the outcome of increased water availability [10].

Investigating intercropped systems of black walnut–maize and red oak–maize, Jose et al. [11] found that water competition with tree roots and not shading was the main limiting factor for maize productivity. Many others also argue the importance of water competition/complementarity in intercropped systems as crucial for system productivity [11–14]. Depending on soil hydrological characteristics, tree and crop species and their root distribution, seasonal requirements, and the level of competitiveness, tree–crop interactions can vary significantly. Nevertheless, when soil water is scarce, trees can 'prefer' to uptake water from deeper soil layers, reducing competition with crops in the upper layers and allowing for complimentary water use in the system [15]. Such complementarity was observed between Populus trees and corn and apple trees and corn, where corn extracted water from 0–60 cm, and primary water sources for trees were below 60 cm of soil depth [16,17]. Similarly, Bai et al. [8] found that in intercropped systems with apricot, crops extracted the water not used by apricot trees from the upper layers of the soil, resulting in a water use advantage of 39%, 51%, and 34% for intercropped systems with peanuts, millet, and sweet potatoes, respectively, in comparison to the monoculture systems.

Land and water use advantages in intercropped systems can be expressed using indices of LER—Land Equivalent Ratio—and WER—Water Equivalent Ratio. If LER > 1 and WER > 1, the intercropped system is more productive per unit of land and water, i.e., producing the same yield in sole systems would require extra land and water.

A more recent interest of arable farmers in switching to fruit growing provides a good opportunity for introducing intercropped orchard systems as a way of intensifying production and gaining a steady flow of income while trees become mature enough to produce yield. The aim of our research was to investigate the land and water productivity of walnut orchards (*Juglans regia* L.) intercropped with buckwheat (*Fagopyrum esculentum* Moench.)—a summer crop with high water needs—and winter barley (*Hordeum vulgare* L.)—a crop with relatively low water needs. Intercrops yields and water productivity were compared with monoculture systems, as well as between older and younger orchard systems.

2. Materials and Methods

2.1. Field Experiments and Systems Description

Field experiments were conducted during 2019 and 2020 on two locations in eastern Croatia: Đakovo (45°18′24.09″ N, 18°26′20.5″ E) and Ivankovo (45°18′53.71″ N, 18°40′21.49″ E). Đakovo's site elevation is 111 m above sea level, and the Ivankovo site is 88 m above sea level. Soil type on both sites is luvisol pseudogley on loess, and the effective soil depth is 1500 mm. Soil preparation before buckwheat and barley sowing was uniform on both sites and for both monoculture and intercropped systems. It consisted of plowing up to 30 cm and soil leveling. Soil physical and chemical properties for different years, sites, and systems are given in Tables 1 and 2, respectively.

Table 1. Soil physical properties.

Location	Depth (cm)	Particle Size Distribution (%) Sand	Clay	Silt	Texture Class	Bulk Density (g cm^{-3})
Đakovo	0–40	2.95	25.9	71.15	silt loam	1.51
	40–60	2.72	28.07	69.21	silty clay loam	1.56
	60–125	2.57	27.72	69.71	silt loam	1.56
Ivankovo	0–40	3.7	17.96	78.34	silt loam	1.54
	40–60	2.73	29.12	68.15	silt loam	1.6
	60–110	2.02	34.02	63.96	silty clay loam	1.6
	110–140	2.43	29.95	67.62	silt loam	1.6

Table 2. Soil chemical properties.

Year	Soil Properties	Đakovo Monoculture	Đakovo Intercropped Orchard	Đakovo Orchard	Ivankovo Monoculture	Ivankovo Intercropped Orchard	Ivankovo Orchard
2019 Buckwheat	pH($H_2$0)	5.6 ^{b}	6.2 ^{b}	6.0 ^{b}	6.0 ^{b}	7.3 ^{a}	5.9 ^{b}
	AL-P_2O_5 mg/100 g	10.3 ^{bc}	7.0 ^{bc}	5.9 ^{c}	13.6 ^{ab}	17.7 ^{a}	19.1 ^{a}
	AL-K_2O mg/100 g	12.4 ^{c}	13.0 ^{c}	14.4 ^{c}	16.5 ^{bc}	19.1 ^{b}	24.9 ^{a}
	SOM%	1.6 ^{a}	1.6 ^{a}	1.6 ^{a}	1.7 ^{a}	1.6 ^{a}	1.5 ^{a}
2020 Barley	pH($H_2$0)	5.6 ^{c}	5.9 ^{bc}	6.3 ^{b}	6.2 ^{b}	6.9 ^{a}	5.7 ^{c}
	AL-P_2O_5 mg/100 g	9.5 ^{bc}	6.9 ^{c}	9.6 ^{bc}	14.9 ^{a}	14.5 ^{a}	12.1 ^{ab}
	AL-K_2O mg/100 g	11.8 ^{c}	14.6 ^{bc}	18.5 ^{a}	18.5 ^{a}	19.5 ^{a}	17.6 ^{ab}
	SOM%	1.6 ^{c}	2.0 ^{ab}	2.2 ^{a}	1.4 ^{c}	1.6 ^{c}	1.7 ^{bc}

Means denoted by different letters (^{a}, ^{b} and ^{c}) indicate significant differences between systems ($p < 0.05$; Tukey's test).

Each location consisted of three plots: (a) control plot of monoculture crop; (b) sole walnut orchard; (c) intercropped walnut orchard. Tree rows in both locations were oriented north–south.

In Đakovo, the walnut orchard was 12 years old with 8 m alleys between grafted walnut trees. Within intercropped orchard, crops were sown in strips of 6 m in width, giving a crop area of 0.75. Buckwheat was grown during the summer of 2019. It was sown on 27 May and harvested on 3 September. Barley was sown on 28 October of the same year and harvested on 30 June 2020. Walnut orchard in Ivankovo was 5 years old with a distance between tree rows of 10 m and crop strips width of 8 m, resulting in a crop area of 0.8. Buckwheat was sown on 10 June and harvested on 17 September 2019. Barley was then sown on 3 November and harvested on 10 July. Neither fertilization nor irrigation was applied to any of the experimental plots.

2.2. Yields Determination

Crop yields were determined by harvesting plants from a 1 m^2 area on 16 random points for each system, separating and weighing the grain, and calculating the grain weight per 1 ha area to obtain total yields in kg ha^{-1}. To account for the bare, unsown area in intercropped orchards (tree row strip), determined crop yields (per crop area) were multiplied by 0.75 (Đakovo) and 0.8 (Ivankovo) to obtain yields per total area. In Đakovo, walnut yields were determined by collecting fruit from each walnut system and weighing it: in 2019 as a kernel in a shell and in 2020 as a nut in a green husk. Since the orchard in Ivankovo is young and has not started yielding significantly, the fruit yield was not determined there.

2.3. Soil Water Content

Soil volumetric water content throughout growing seasons was derived from soil water potential data. The matric potential of soil water was recorded continually using Watermark sensors (Environmental Measuring Systems s.r.o., Brno, Czech Republic) on each site. Additional sensors were carefully placed in the soil samples ring from each site for calibration. These were then soaked in water until fully saturated, left for a few days, and then removed from the water onto a dry tray. The measurements of water matric potential were recorded from sensors, and the sample rings were weighted every few hours until completely dry. From determined gravimetric water content and water potential readings, regression equations were obtained, allowing the exploration of volumetric water content for each site throughout growing seasons. However, due to technical issues with sensors on experimental plots in fall 2019, water content data during barley vegetation are missing. In order to calculate water use during barley vegetation, soil water content at sowing and harvest was then determined manually by collecting soil ring samples and determining gravimetric water content. The soil water measurements were recorded for 30, 60, and 90 cm of soil depth, and the average values were used to interpret the results. Although these may not represent total water use in intercropped systems with trees, they probably represent a significant part of the water available and used by crops and trees.

2.4. Hydrothermal Coefficient of Water Protection

Temperature and precipitation data were obtained using Vantage Pro2 meteorological stations (Davis Instruments Corporation, Hayward, CA, USA) placed in both experimental locations. The meteorological station measured hourly data, which was then summed for the total daily amount of precipitation and averaged for the daily average temperature (Figure 1).

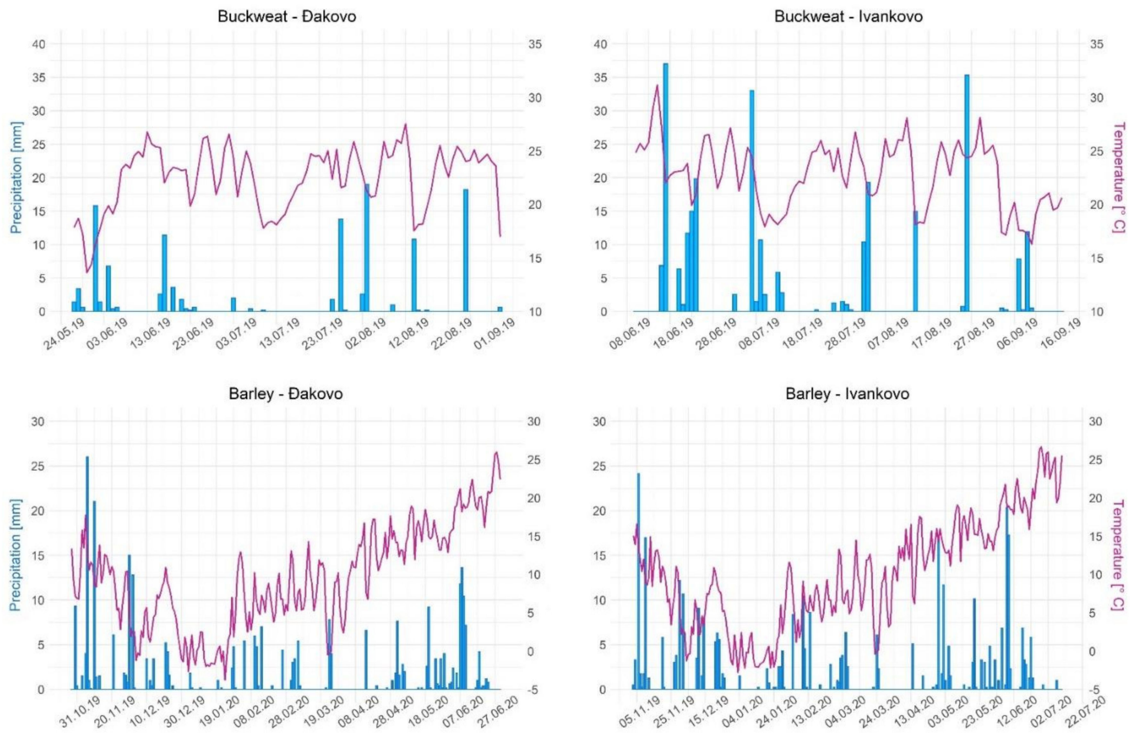

Figure 1. Measured temperature and precipitation during buckwheat and barley vegetation.

To describe the comprehensive effect of temperature and humidity conditions, the hydrothermal coefficient (K) was calculated monthly during crops vegetation; K = 10 * monthly sum of rainfall [mm]/number of days * average daily air temperature in a month [°C].

Interpretation of the hydrothermal coefficient according to Selyaninov [18]:

1. $K > 1.5$: excessive humidity for most plants;
2. $1 < K < 1.5$: humidity sufficient for most plants;
3. $0.5 < K < 1.0$: insufficient humidity for most plants;
4. $K < 0.5$: drought.

2.5. Water Productivity Determination

Soil water content and precipitation data were used in the water balance equation [19] for calculating growing season evapotranspiration (ET_C, mm), which represents actual water use (WU, mm) of the studied systems:

$$WU = P + S_1 - S_2$$

where P is the amount of rainfall (mm) during the crop growing season, S_1 is the water content (mm) within 0–100 cm soil depth at crop sowing, and S_2 is the water content at crop harvest. Water runoff and capillary rise have not been considered because experimental fields are quite flat, and the water table is low (below 10 m). Due to the presence of a poorly permeable Btg subsoil horizon with higher clay content on both sites, downward drainage is negligible and has therefore been excluded from the water balance equation. Since crop and walnut roots overlap in intercropped systems, water use was not partitioned for each plant species but for the system as a whole. It was determined by averaging WU measurements from the middle of an intercropped alley and within tree rows.

Water productivity (WP, kg ha^{-1} mm^{-1}) was calculated as the ratio of the yield and the previously defined water use:

$$WP = Y/WU$$

where Y is crop or fruit yield (kg ha^{-1}), and WU is the actual water use per unit area of a system (mm).

2.6. Land and Water Equivalent Ratios

The land equivalent ratio (LER) was estimated from crop yields and walnut fruit yields to characterize land use efficiency. The LER can be defined as the ratio of the area under monoculture production to the area under intercropping needed to give equal yields at the same management level [20]. It is calculated as the ratio of tree yield from intercropped system to the tree monoculture yield, plus the ratio of crop yield from intercropped system to the crop monoculture yield [21]. In other words, it is the sum of relative walnut and crop yields:

$$LER = pLER_W + pLER_C = Y_{int,W}/Y_{mono,W} + Y_{int,C}/Y_{mono,C}$$

where $pLER_W$ and $pLER_C$ are so-called partial LERs of walnut and crop, i.e., relative yields of species in the intercropped system. $Y_{int,W}$ and $Y_{int,C}$ are yields of walnut and crop in the intercropped system, respectively, and $Y_{mono,W}$ and $Y_{mono,C}$ are walnut and crop yields in monoculture plot, respectively. When LER ≤ 1, there is no agronomic advantage of intercropping over sole cropping, but when LER is >1, production in the intercropped system is higher than in the separate sole systems, meaning that producing the same yields in monoculture systems would require more land area.

To assess the water use advantage of the intercropped system, the water equivalent ratio (WER) was defined by analogy to LER. WER was calculated as the ratio of intercropped walnut WP to the walnut monoculture WP plus the ratio of crop WP in the intercropped system to the crop monoculture WP:

$$WER = pWER_W + pWER_C = WP_{int,W}/WP_{mono,W} + WP_{int,C}/WP_{monoC}$$

Similar to LER, WER values quantify the amount of water needed in monoculture plots for walnut and crops to achieve the same yield as produced with one unit of water in the intercropped system. WER > 1 indicates a water use advantage for the intercropped system, meaning that yields in the intercropped system are produced with less water than needed for the same yields in monoculture plots. Therefore, WER was used to determine whether water was used more efficiently in intercropping than in traditional sole cultivation [22]. If both LER > 1 and WER > 1, then the intercropped system requires less land and less water than monoculture cultivation.

Since walnuts in Ivankovo still have not produced significant fruit yield, LER and WER values were determined for the Đakovo site only.

2.7. Statistical Analysis

Statistical analysis of the obtained data was conducted in R software [23] using Analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) post hoc test. Non-parametric alternative tests were applied where appropriate—Welch's ANOVA in case of significant variance heterogeneity or/and unbalanced data, followed up by Games-Howell post hoc test. Differences between locations and systems were tested for soil chemical properties, yields, LERs, water productivity, and WERs. Regression analysis was used to check whether soil chemical properties influenced yield and water productivity. No significant correlations were found, so these results are not presented in detail.

3. Results

3.1. Yields and Land Equivalent Ratios

Unexpectedly, in Ivankovo, the intercropped buckwheat yield was higher than the monoculture buckwheat yield: 1985 and 1689 kg ha^{-1}, respectively (Figure 2a). This resulted in a high average pLER$_C$ of 1.17 (Table 3).

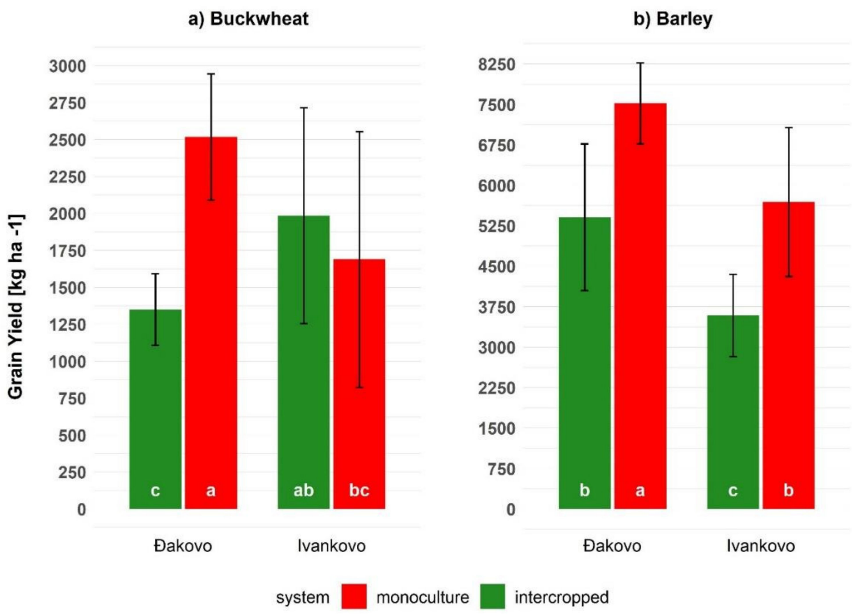

Figure 2. Grain yields of (**a**) buckwheat and (**b**) barley in monoculture and intercropped systems (per total area). Bars denoted by different letters (a, b and c) indicate significant differences between systems ($p < 0.05$; Tukey's test). Vertical bars represent standard deviation from the mean value.

Table 3. Land equivalent ratios.

Location	Crop	$pLER_C$	$pLER_W$	LER
Đakovo	Buckwheat	0.54 ± 0.09^{b}	0.51	1.05 ± 0.09^{b}
	Barley	0.72 ± 0.18^{b}	0.81	1.53 ± 0.18^{a}
Ivankovo	Buckwheat	1.17 ± 0.43^{a}	-	-
	Barley	0.63 ± 0.13^{b}	-	-

Means denoted by different letters (^{a} and ^{b}) indicate significant differences between systems ($p < 0.05$; Tukey's test). $pLER_C$ (crops) differences were tested for both species together and LER for Đakovo between two years. The significance of the difference between walnut $pLER_W$ was not tested as there was only one data point for each system.

In Đakovo, the situation was the opposite—the monoculture had a significantly higher buckwheat yield than the intercropped system (2517 and 1349 kg ha^{-1}, respectively), and it was the highest observed buckwheat yield (Figure 2a). This resulted in a relatively low buckwheat $pLER_C$ of 0.54.

Walnut fruit yields in Đakovo showed significant differences between the first and second half of the orchard long before intercropping. The first half always had lower yields, and intercropping between its rows was a way of increasing the productivity of that part of the orchard. Correspondingly, 2019 was no exception—the intercropped part of the orchard produced only 51% of sole orchard fruit yield (378 and 746 kg ha^{-1}, respectively).

The partial crop and walnut LERs gave a total LER of 1.05, which means the intercropped system was, on average, 5% more productive in terms of land use efficiency than growing buckwheat and walnut separately (Table 3).

On the other hand, barley yielded significantly higher in monoculture in both locations: 7519 kg ha^{-1} in Đakovo and 5688 kg ha^{-1} in Ivankovo (Figure 2b). Furthermore, barley intercropped yield in Đakovo (5407 kg ha^{-1}) resulted in higher $pLER_C$ than in Ivankovo (3586 kg ha^{-1}): 0.72 and 0.63, respectively (Table 3).

Walnut yield in Đakovo in 2020 amounted to 2136 kg ha^{-1} in the intercropped orchard and 2625 kg ha^{-1} in the sole walnut stand, which gave higher a walnut $pLER_W$ (0.81) than the previous year. This led to a higher average LER of 1.53, meaning that the intercropping system of walnut and barley was 53% more productive per unit of land area than its respective monoculture systems and 48% more productive than the walnut–buckwheat system (Table 3).

3.2. Soil Water Content and Air Hydrothermal Conditions

During both years, Đakovo generally had more frequent and longer dry periods than Ivankovo, especially during buckwheat vegetation. There was no significant difference in air temperature between the locations. However, Ivankovo had more rain (263 mm during buckwheat vegetation and 352 mm during barley vegetation) than Đakovo (122 mm and 294 mm during buckwheat and barley vegetation, respectively) (Figure 1). This resulted in an overall higher hydrothermal coefficient for Ivankovo during both years (Figure 3).

In 2019, during buckwheat vegetation, the soil water content in monoculture systems did not differ significantly between the two locations. However, the differences were pronounced between systems in both locations. In Ivankovo, buckwheat in the intercropped system had higher water content through vegetation than buckwheat in the monoculture plot. Sole orchard also had lower soil water content than the intercropped orchard, especially during the second half of the summer (Figure 3b). On the other hand, in Đakovo, the soil water content in the intercropped system was lower than in the monoculture during the critical vegetation stage for buckwheat—flowering. In addition, the soil water content in the sole orchard was higher than in the intercropped orchard (Figure 3a).

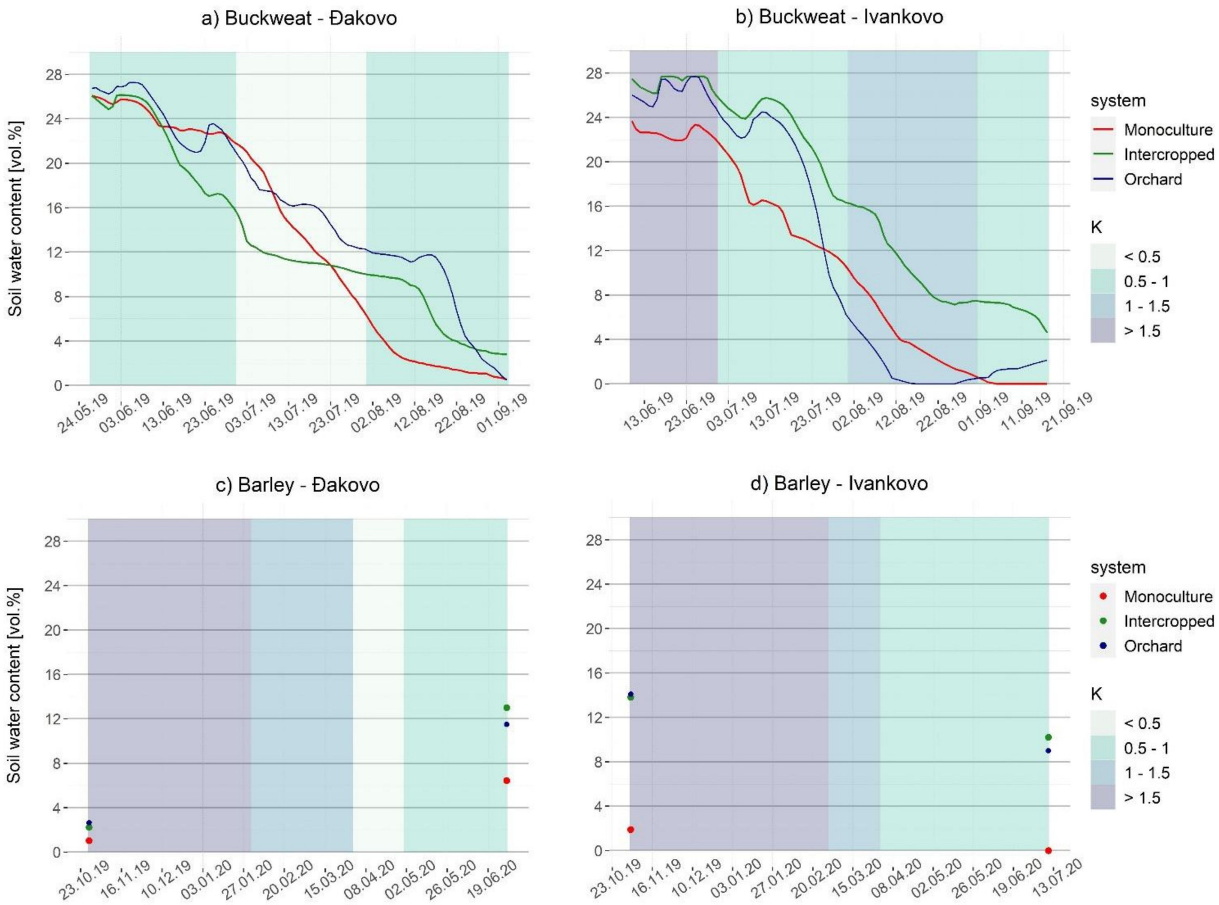

Figure 3. Soil water content and hydrothermal coefficient (K) during crops vegetation periods: (**a**) buckwheat in Đakovo, (**b**) buckwheat in Ivankovo, (**c**) barley in Đakovo, (**d**) barley in Ivankovo. Measurements during barley vegetation were taken at sowing and harvest.

Data on soil water content during barley vegetation were not recorded continuously. Nevertheless, the measurements at sowing and harvest showed higher water content in intercropped systems compared to monoculture barley plots. In both locations, sole walnut orchards initially had about the same amount of water as intercropped systems and slightly less at crop harvest (Figure 3c,d).

3.3. Water Productivity and Water Equivalent Ratios

During 2019 in both locations, the intercropped systems used less water (WU) than their respective monoculture systems, which indicates that intercropping reduced evapotranspiration (Figure 4a). However, since grain yield in Đakovo was significantly reduced, water productivity (WP) of intercropped buckwheat was also lower than monoculture buckwheat. The average $pWER_C$ amounted to 0.57. The same was observed for walnut WP—sole orchard walnuts were more productive per unit of water than intercropped trees. Nevertheless, this system was, on average, 12% more water-efficient (WER) than separate walnut and buckwheat (Table 4).

On the other hand, in Ivankovo, high buckwheat $pWER_C$ was consistent with $pLER_C$, and it showed that buckwheat in the intercropped system was more water-productive than monoculture buckwheat (Table 4).

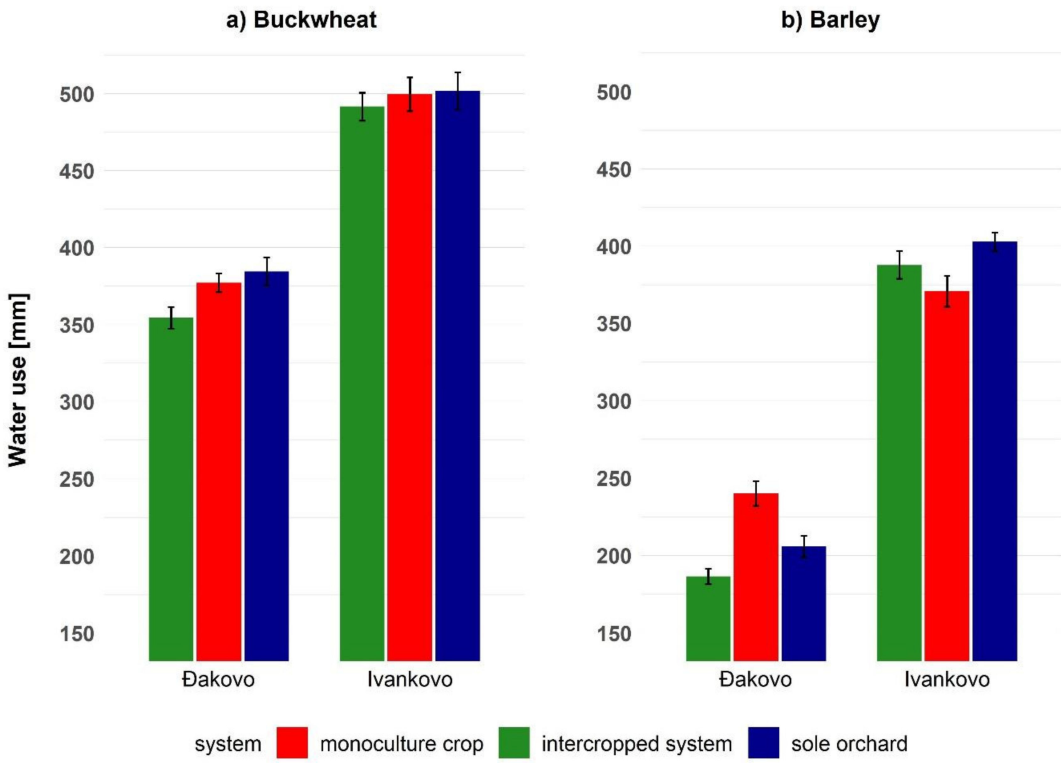

Figure 4. Water use, i.e., ET_C in monoculture crop systems, intercropped systems, and sole walnut orchards during crops vegetation periods: (**a**) buckwheat, (**b**) barley. Vertical bars represent standard deviation from the mean value.

Table 4. Water productivity and water equivalent ratios.

Year/Crop Species	Location	System	WP (kg ha^{-1} mm^{-1})	pWER	WER
2019 Buckwheat	Ivankovo	Monoculture crop Intercropped crop	3.38 ± 1.73 [b] 4.04 ± 1.48 [b]	1.19 ± 0.44 [a]	-
	Đakovo	Monoculture crop Intercropped crop Sole walnut Intercropped walnut	6.68 ± 1.13 [a] 3.81 ± 0.68 [b] 1.94 1.07	0.57 ± 0.10 [b] 0.55	1.12 ± 0.10 [b]
2020 Barley	Ivankovo	Monoculture crop Intercropped crop	15.34 ± 3.73 [b] 9.25 ± 1.96 [c]	0.60 ± 0.13 [b]	-
	Đakovo	Monoculture crop Intercropped crop Sole walnut Intercropped walnut	31.32 ± 3.13 [a] 28.99 ± 7.30 [a] 12.76 11.45	0.93 ± 0.23 [a] 0.90	1.83 ± 0.23 [a]

Means denoted by different letters ([a], [b] and [c]) indicate significant differences between systems ($p < 0.05$; Tukey's test). WP was tested for each species separately, $pWER_C$ for both species together, and WER for Đakovo between two years. The significance of the difference between walnut WP and $pWER_W$ was not tested as there was only one data point for each system.

Intercropping with barley was significantly more successful in Đakovo than Ivankovo. While barley in Ivankovo achieved a $pWER_C$ of 0.60, in Đakovo, it amounted to a high 0.93, on average (Table 4). Furthermore, since the intercropped system in Đakovo used less water than the sole orchard (Figure 4b), and fruit yield was not significantly reduced, walnut trees also achieved high $pWER_W$. This led to the intercropped system with walnuts and barley being highly efficient in water utilization, showing that sole systems would need, on average, 83% more water to achieve the same yields as in the intercropped system

(Table 4). Consistently with LER, this system was also more water-efficient (WER) than walnut–buckwheat intercropped orchard by 70%.

4. Discussion

Our previous research [24] showed that intercropping walnut orchards could be a profitable transition solution for arable farmers aiming to switch to walnut fruit production. In addition, there are additional income opportunities for fruit growers from intercropping already established orchards. However, fruit growers' higher inputs and labor needed to be adopted pose a great risk under the uncertainty in the productivity of different crops influenced by mature walnut trees. Our study aimed to investigate environmental aspects of such systems, i.e., how productive and water-efficient can buckwheat (summer crop) and barley (winter crop) be under an older walnut orchard with a narrower alley, in contrast to a younger one, with wider crop alleys.

We observed great differences in regard to crop species and tree age/density. Namely, with respect to site-specific monoculture systems, intercropped buckwheat seemed to perform significantly better in the younger orchard and barley in the older one in terms of both yield and water productivity.

The walnut–buckwheat system in Đakovo achieved an average LER of 1.05 and a WER of 1.12. However, if we account for the deviations from these mean values, it is questionable if this system could be more productive per units of land and water than growing buckwheat and walnuts separately. Walnut trees in the intercropped system produced only 51% of sole orchard fruit yield; however, this part of the orchard always had lower yields, even before introducing intercrops, so it is not possible to ascribe a definite buckwheat effect to these observations. During the buckwheat vegetation, arid hydrothermal conditions were observed in Đakovo. Some studies suggest that shading by trees can mitigate the adverse effects of drought by reducing heat stress [25–27], retaining the water from evaporation and preserving more water for plant transpiration [28]. Even though the intercropped system probably did lower the evaporation, our results suggest that this effect was negligible as buckwheat's high water demands, especially during the seedling stage and flowering, were not met in the intercropped system where competition with walnuts was too intense. Water stress during this period has a high impact on lowering the number of flowers and, consequently, the number of seeds and total yield per unit area [29]. In addition, radiation transmittance reduced by large walnut canopies probably caused light stress and had a negative effect on buckwheat yield [12].

Contrary, in Ivankovo, where walnut trees are spaced widely and its smaller canopies do not overcast a significant shading on the understory, intercropped buckwheat achieved higher yield and water productivity than in the monoculture plot. Generally, Ivankovo had more favorable climate conditions during buckwheat vegetation than Đakovo and competition between trees and crops may not be significant if water is not scarce [15,30]. Our results show that young walnut trees did not interfere with buckwheat's water consumption, as opposed to observations in Đakovo. In addition, the higher water content in the intercropped orchard, as opposed to monoculture plot and sole orchard, implies that buckwheat and walnut trees efficiently shared the water that would otherwise evaporate from the soil surface. Unexpectedly high buckwheat yield in the intercropped system could not be explained by differences in soil properties between observed systems, and it is difficult to describe the mechanism behind complementary interactions in this system without detailed research of belowground processes and root distribution. Furthermore, even though it is possible that buckwheat was the dominant species in this system, it was not possible to quantify its impact on walnut yield and water productivity since the young walnut orchard has not produced any yield yet.

Due to both high crop and walnut relative yields, the intercropped system of walnut and barley in Đakovo achieved high LER and WER. Our results showed that this system was, on average, 53% more land-productive and 83% more water-productive than separate monoculture systems, and it was also 47% more productive per unit of land and 71%

more water-productive than the walnut–buckwheat system. As previously mentioned, the intercropped part of the orchard always gave significantly lower fruit yields in previous years, even before introducing arable intercrops. However, in 2020, the difference was not that significant. Improved walnut pLERW (0.81) and pWERW (0.90) show that either subtle changes in soil properties of the intercropped orchard are positively affecting walnut productivity or there may be some underlying positive effect of barley.

In theory, there may be temporal complementarity between winter crops and walnut trees. Namely, walnut is a late leafing deciduous species, so shading by its canopy that occurs during later barley development may not have a critical limiting effect on barley yield. Furthermore, barley is a C3 plant, which means it is less susceptible to negative effects of shading, as only 50% of full sunlight is enough for the plant to become fully light-saturated [4]. Similarly, belowground, walnut fine root production peaks during the summer months [31,32], and by this time, most winter crops, including barley, are already fully developed and have captured most of the nutrients and water from the soil [5]. In favor of this temporal complementarity hypothesis are findings by Liu et al. [33]. The authors showed that walnut consumes most of the water in the fruit expansion stage during the summer months, and the sources of that water are mostly deeper soil layers.

Although the soil water content at sowing and harvest showed that intercropped systems of walnut and barley had more water than monoculture barley, it is unknown how it was distributed through vegetation and how it was shared between barley and walnut. Still, barley yield and water productivity in intercropped systems in both locations were lower than in their monoculture systems. In addition, barley pLERC and pWERC were lower in Ivankovo than in Đakovo. Shading by larger tree canopies in Đakovo probably affected barley productivity. However, in Ivankovo, where walnut trees are spaced widely and smaller canopies do not overcast significant shading on the understory, a belowground competition was probably the main driver of the walnut–barley system's productivity, and it may be correlated to a rooting pattern. Generally, tree water consumption increases with tree age, so the root system tends to grow deeper to meet increasing water requirements [34]. Accordingly, younger trees prefer to extract water from shallower soil layers in the cropping zone, where most of their roots are [35]. Consequently, stronger competition for water and nutrients can occur in intercropped systems and thereby cause a more significant reduction in crop yields. Zhao et al. [30] observed that most of the lateral roots of 4-year-old jujube trees were spread in up to 30 cm of soil depth, while older jujube trees had a majority of their lateral roots around 60 cm of soil depth. This may have caused a greater reduction in understory peanut yield under younger jujube trees. Furthermore, the soil in Ivankovo has a higher bulk density, and it is generally more compact than the soil in Đakovo, especially in the subsoil layer. Such soil can limit trees' vertical root growth and cause more pronounced lateral spreading of walnut roots, which then interfere with crops roots. On the other hand, considering this hypothesis and high buckwheat yield in the intercropped orchard in Ivankovo, it seems that buckwheat roots, despite low total mass, have a good absorption power [36] and have ensured high productivity, even in competition with young walnut trees.

The water balance equation showed that the walnut–barley intercropped system in Ivankovo used more water than the monoculture barley and much more than the Đakovo systems. In fact, the WU values were consistently greater in Ivankovo than in Đakovo, and these differences can partially be explained by differences in the amount of rainfall and other climatic conditions, which may have been different between the two locations. Furthermore, our observations showed that a decrease in water use (i.e., ETC) in intercropped systems compared to crop monoculture and sole orchard systems was more pronounced in Đakovo. Liu et al. [16] found that the dense crown of Populus in intercropped system decreased radiation and wind speed, which led to a higher contribution of plant transpiration to total ET rather than soil evaporation. Even though the differentiation between plant transpiration and soil evaporation was not assessed in this study, considering our observations as well as previous studies, it seems that shading by large canopies of walnut trees did contribute to the reduction in soil evaporation [37]. Another possible effect that may help intercropped systems retain more water in the topsoil is hydraulic lift by deeper tree roots [30]. Additionally, a higher ET was observed during buckwheat vegetation, which can be ascribed to warmer summer conditions and higher tree transpiration rates due to increased walnut growth during these months.

5. Conclusions

Intercropping with trees, through various mechanisms, can ensure maximum utilization of available soil water, which, in theory, can increase yields without the need for additional irrigation. However, previous research, including ours, confirms that intercropping with trees is not a universal solution for achieving high yields and improved water utilization and that species selection and system design can be crucial factors. Considering the positive effect of trees on microclimatic conditions, our observations suggest that the primary limiting factor in older and denser orchards may be light, especially for summer crops sensitive to reduced radiation transmittance. On the other hand, in younger orchards with smaller canopies but shallower tree roots, water competition has a more significant effect on intercrop performance than the lack of light. Although these competitive interactions can be reduced by proper tree management, such as branch pruning or even root pruning, those can be labor-intensive and expensive and should be repeated frequently. Therefore, it is necessary to ensure proper tree spacing when establishing intercropped systems, but good practice could also be to sow competitive crops in the first years of intercropping. Highly competitive crop roots could suppress tree roots' lateral spreading and enhance their vertical growth, ensuring belowground spatial complementarity between future intercrops and trees. In older, mature orchards, reduction in competition can be based on ensuring temporal complementarity by choosing winter crops, such as barley.

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Naslova rada: Ecological and Agronomic Benefits of Intercropping Maize in a Walnut Orchard—A Case Study

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Ecological and Agronomic Benefits of Intercropping Maize in a Walnut Orchard—A Case Study

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Abstract: The incorporation of trees on traditional agricultural land has the potential for providing beneficial conditions for understory crops by altering the microclimate. Under these assumptions, we conducted a study on maize productivity intercropped in a 14-year-old walnut orchard by measuring growth and yield parameters, and water and nutrient uptake. Overall, we found that walnut trees decreased maximum air temperature and increased air humidity, especially during hot summer months characterized by precipitation deficit. A 30% reduction in maize yield per total area was a result of significantly reduced plant density, which could be a walnut-specific effect due to juglone excretion. Productivity per plant increased as shown by a significantly higher harvest index and 1000 kernel weight. No meaningful differences were found in terms of maize grain nutrient productivity, nutrient recovery, or nutrient use efficiency. On the systems level, we observed an advantage of the walnut-maize system compared to its respective monoculture systems—land and water equivalent ratios showed that for gaining the same yields as in intercropped system, walnut and maize grown separately would need 32% more land and 31% more water. Our study implies there are some beneficial outcomes to growing maize with trees, although further research should focus on investigating walnut as an option, due to its possible allelopathic effects.

Keywords: agroforestry; intercropped orchard; walnut; maize; water equivalent ratio; land equivalent ratio; nutrient efficiency

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1. Introduction

The trend of rising temperatures under climate change is well evidenced and many future climate projections indicate that the continuation of this trend is inevitable [1]. Generally, many regions will face warmer and drier conditions during summer, which insinuates a high risk for agricultural production. Maize (*Zea mays* L.), one of the most important crops, might be especially vulnerable [2], even though it favors relatively higher temperatures than other staple crops. Outside breeding efforts to produce more heat-stress resilient hybrids, maize adaptation will need to deal not only with increased temperature averages but also with the increasing frequency of extreme climate conditions [3]. Excellent potential for mitigating these conditions has been shown by introducing trees to traditional arable land and establishing agroforestry systems. Trees can modify the microclimate by influencing radiation flux, reducing temperature oscillations and wind strength, and increasing relative air humidity. These changes lead to a reduction of evapotranspiration and the improvement of water utilization for such systems, and ultimately, more stable conditions for crops grown underneath the trees [4]. Intercropping arable crops between trees provide many ecosystem services [5], and one of the most important potentials of these systems is the reduction of reliance on chemical inputs, via better utilization of soil nutrients [6]. Trees in agroforestry systems may promote advantages in nutrient acquisition of understory crops by reduction of losses via safety nets, uplift of deep soil nutrients, changes in chemical processes at the rhizosphere by root activity, and the addition of nitrogen from the atmosphere in the case of N fixing trees [7]. However, many factors affect these processes and the balance between complementarity and competition for resources between species is crucial for the overall productivity of agroforestry systems. Probably the greatest concern for intercropping maize with trees is the reduction of incoming radiation under the shade of trees. Maize, as a C4 plant, is sensitive to reduced radiation, and the reduction of biomass and yield under shading is anticipated [8]. However, some studies have concluded that light competition is not a significant factor for the reduction of maize yields in agroforestry when tree lines follow a N–S orientation [9–11], and some studies in Africa have found even higher maize yields in agroforestry compared to monoculture maize [12,13]. Still, the extent of shade and its effect on understory crop productivity depends also on the tree species, age and morphology. In the case of high trees with wide or converging canopies, there will be little advantage of the N–S orientation. Another factor is the region, i.e., climate. The positive effects of trees which have been found in tropical regions may have the completely opposite effect in temperate regions. Common walnut (*Juglans regia* L.), also called English or Persian walnut, is cultivated around the world. It produces kernels with great nutritional value, but it also produces high-quality timber [14]. The suitability of walnut for agroforestry systems lies in its morphological and phenological features: its irregular, half-open crown allows more light to reach the understory, and its late leafing delays shading on intercrops, which is the basis of temporal complementarity in systems with winter crops. At the same time, this trait could be a competing factor in systems with summer crops. Furthermore, the walnut tree has a long and not very fibrous taproot, which has the potential to partially eliminate below-ground competition with crops [10,15]. However, these features can vary across different environmental conditions, soil types, pruning management processes, etc. Another important aspect to consider for intercropping with walnut trees is allelopathy. Namely, walnut trees produce a variety of organic substances that can have inhibitory effects on plants grown nearby, but the most notable one is juglone (5-hydroxy-1,4-naphthoquinone). Juglone is found in all tree organs but is especially abundant in leaves, fruit hulls, and roots [16].

Considering all of the above, our study aimed to quantify the potential microclimatic benefits of intercropped walnut orchards and evaluate whether they can aid maize growth under the hot and dry summers of temperate Europe, despite anticipated competition with walnuts. The novelty of our research lies in a system-level investigation, as well as a detailed study of maize growth, and water and nutrient-related productivity. It was conducted by measuring and analyzing (i) microclimate parameters; (ii) soil moisture; (iii) maize phenology, growth, yield, and nutrient uptake, and (iv) the land and water productivity of the system.

2. Materials and Methods

2.1. Field Experiments and Systems Design

Field experiments were conducted in 2021 in Eastern Croatia near the city of Đakovo (45°18′24.09′′ N, 18°26′20.5′′). The site elevation is 111 m above sea level, with soil type luvisol pseudogley on loess, and an effective soil depth of 1500 mm. This area has a continental climate of warm summers and cold winters, with a mean annual rainfall of between 600 and 1000 mm, relatively evenly distributed throughout the year.

The experiment consisted of three plots, each approximately 1.3 ha: (a) a control plot of an arable field with only maize (further referred to as monoculture maize system); (b) a sole walnut orchard; (c) a walnut orchard intercropped with maize.

The orchard was 14 years old at the time of the experiment, with 8 m alleys between and a distance of 7 m within the rows of walnut trees (*Juglans regia* L.). Tree density was uniform for both the sole and intercropped orchards. Tree row orientation was N–S, and trees were pruned every year in March. In 2021, trees were on average 5.5 m high, with an average canopy width of 5 m. All the walnut trees received organic fertilization in 2015 and foliar topdressing yearly. Within the intercropped orchard, maize was sown in strips of 6 m in width, resulting in a crop area of 75%. Maize (hybrid PP9911) was sown on 26 April

2021 with a 75 × 19 cm interspace. There were eight maize rows between walnut trees. Maize was harvested on 14 October 2021. All systems were managed following organic agriculture principles. Soil management and fertilization were uniform for both maize plots and no irrigation was applied. Before maize sowing, the green manuring principle was applied (plowing of buckwheat in the flowering stage). During the 3–5 leaves stage, liquid N fertilizer acceptable in organic farming was applied to both the intercropped maize and arable field maize.

2.2. Meteorological Data

Temperature and humidity data were obtained from Tinytag (Gemini Data Loggers, West Sussex, UK) devices placed between maize rows at crop height. The height position of these devices was adjusted during vegetation to follow the growth of maize plants. Precipitation data were measured using the Vantage Pro2 meteorological station (Davis Instruments Corporation, Hayward, CA, USA).

To describe the broad effect of temperature and humidity, the hydrothermal coefficient (K) was calculated:

$$K = 10 * \text{sum of rainfall [mm]}/\text{number of days} * \text{average daily air temperature [C]}.$$

Interpretation of the hydrothermal coefficient according to Selyaninov [17] was based on the following:

1. $K > 1.5$: excessive humidity for most plants;
2. $1 < K < 1.5$: humidity sufficient for most plants;
3. $0.5 < K < 1.0$: insufficient humidity for most plants;
4. $K < 0.5$: drought.

2.3. Soil Water Content

Soil volumetric water content was derived from soil water potential data. The matric potential of soil water was recorded using Watermark sensors (Environmental Measuring Systems s.r.o., Brno, Czech Republic) on each plot. Due to technical difficulties with the sensors, data was recorded during 10-day periods around each observed stage (see Section 2.4). Sensors were previously calibrated as described in Žalac et al. [18]. The soil water measurements were recorded for 10, 30, 60, and 90 cm of soil depth.

2.4. Sampling, Measurements, and Analysis

Ten maize plants were sampled at random across the width of the alley, four times during maize development: at the five leaves stage (V5), during the blister stage (R2), during the dough stage (R4), and at harvest (H). Plant samples were measured for height and dried in the oven at 105 °C for the first two hours and then at 70 °C until constant weight to determine aboveground dry matter biomass accumulation. The leaf area of a plant was determined by summing up the measurements of each leaf's maximum width ∗ length ∗ 0.75 [19,20]. This value was then multiplied by the number of plants per 1 m^2 to obtain the leaf area index (LAI). A SPAD-502 meter (Soil Plant Analysis Development, Minolta, Japan) was used to obtain so-called SPAD values of greenness, which indicate the relative amount of chlorophyll present in plant leaves (Minolta, 1989). Four soil samples were collected from both the middle of the alley (10 subsamples) and closer to the trees (10 subsamples) at depths of 0–30 and 30–60 cm. Soil chemical analysis included the determination of pH (HRN ISO 10390:2005), organic matter content (OM) (HRN ISO 14235:1998), and concentrations of available nitrogen (mineral N; NO_3^--HRN EN ISO 13395:1998 and NH_4^+-HRN EN ISO 11732:2008), phosphorus (P_2O_5), and potassium (K_2O) following the Egner et al. method (1960). The content of nitrogen, phosphorus, and potassium was determined from plant tissue and grain at harvest.

2.5. Yields Determination

Maize yields were determined by harvesting plants from a 10 m^2 area, separating, drying, and weighing the grain. Total yields were expressed in kg ha^{-1}. To account for the unsown area in intercropped orchards (tree row strip), the determined maize yield (per cropped area) was multiplied by 0.75 to obtain yield per total area. 1000 kernel weight was also reported on a dry matter basis. The harvest index was calculated as the ratio of dry matter grain yield to dry matter total biomass. Walnut fruit yields were determined by collecting nuts from each walnut system and weighing them.

2.6. Land Equivalent Ratio (LER)

LER (land equivalent ratio), which is used to determine the productivity advantage of intercropped systems, was calculated as follows [21]:

$$\text{LER} = \text{pLERW} + \text{pLERM} = \text{Yint,W}/\text{Ymono,W} + \text{Yint,M}/\text{Ymono,M}$$

where pLERW and pLERC are so-called partial LERs of walnut and maize, i.e., relative yields of species in the intercropped system. Yint,W and Yint,M are yields of walnut and maize, respectively, in the intercropped system, and Ymono,W and Ymono,M are walnut and maize yields, respectively, in the monoculture plot. When LER < 1, there is no agronomic advantage of intercropping over sole cropping, but when LER is >1, production in the intercropped system is higher than in the separate sole system, meaning that for production of the same yields as in monoculture systems, intercropping would require less land area.

2.7. Water Use (WU), Water Productivity (WP), and Water Equivalent Ratio (WER)

For calculating growing season evapotranspiration, soil water content and precipitation data were inputs of the water balance equation [22], which represents actual water use (WU, mm):

$$\text{WU} = \text{P} + \text{S1} - \text{S2}$$

where P is the amount of rainfall (mm) during the maize growing season, S1 is the water content (mm) within 0–90 cm soil depth at crop sowing, and S2 is the water content for the same depth at maize harvest. Water runoff and capillary rise have been ignored because the experimental fields were flat, and the water table was low (below 10 m). Due to the presence of a poorly permeable Btg subsoil horizon with higher clay content, downward drainage was negligible and is therefore excluded from the equation. Water use was not partitioned for each plant species, because maize and walnut roots overlap in intercropped systems; instead, it was representative of the system as a whole. Water use was determined by averaging WU measurements from the middle of an intercropped alley and within tree rows.

Water productivity (WP, kg ha^{-1} mm^{-1}) was calculated as the ratio of the yield and the water use of the system [23,24]:

$$\text{WP} = \text{Y}/\text{WU}$$

where Y is maize or walnut fruit yield (kg ha^{-1}) and WU is the actual water use (mm).

Water equivalent ratio (WER) was used to determine if water was used more efficiently in intercropping than in monoculture systems [25], and it was defined analogously to LER. WER was calculated as the ratio of intercropped walnut WP to the walnut monoculture WP plus the ratio of maize WP in the intercropped system to the maize monoculture WP:

$$\text{WER} = \text{pWERW} + \text{pWERM} = \text{WPint,W}/\text{WPmono,W} + \text{WPint,M}/\text{WPmonoM}$$

WER values quantify the amount of water needed in monoculture plots for walnut and maize to achieve the same yield as produced with one unit of water in the intercropped system. WER > 1 indicates a water use advantage for the intercropped system, meaning that yields in the intercropped system are produced with less water than needed for the same yields in monoculture plots. If both LER > 1 and WER > 1, then the intercropped system requires less land and less water than monoculture cultivation.

2.8. Nutrient Indices

For the estimation of nutrient efficiency in observed maize systems, different nutrient indices were calculated. First, nutrient accumulation (nA) was calculated by multiplying total aboveground dry matter by nutrient content to obtain the accumulated nutrient in kg ha^{-1}. GnA is the amount of nutrient accumulated in the dry matter of grain.

Nutrient use efficiency (nUE) was used as an expression of maize grain productivity per amount of nutrient acquired [26]:

$$\text{nUE} = \text{Y/nA (kg ha}^{-1}\text{ [kg total accumulated nutrient ha}^{-1}]^{-1}),$$

where Y is dry grain yield and nA is nutrient accumulation, with n denoting different nutrients—either nitrogen, phosphorus, or potassium.

Nutrient productivity (nP) was calculated as the ratio of grain yield and available soil nutrient content. It is derived from a concept of nutrient-response efficiency [24,26,27]:

$$\text{nP} = \text{Y/Sn (kg ha}^{-1}\text{ [kg soil nutrient ha}^{-1}]^{-1}),$$

where Y is dry grain yield and Sn is available soil nutrient content, with n being N, P, or K.

Nutrient recovery index (GnRI) was used to determine how efficient maize was in relocating available soil nutrient into grain [24,28]:

$$\text{nRI} = \text{GnA/Sn (kg grain accumulated nutrient ha}^{-1}\text{ [kg soil nutrient ha}^{-1}]^{-1}),$$

where GnA is grain nutrient accumulation and Sn is available soil nutrient content, with n being N, P, or K.

These indices were calculated for the three macronutrients analyzed; nitrogen (NUE, NP, NRI), phosphorus (PUE, PP, PRI), and potassium (KUE, KP, KRI).

2.9. Statistical Analysis

Statistical analysis of the obtained data was conducted in R software [29] using analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) post hoc test. Non-parametric alternative tests were applied in the case of non-normal data distribution and/or variance heterogeneity.

3. Results and Discussion

3.1. Microclimate Conditions

Different simulation models for a future climate in Europe predict warmer and drier conditions with increased risk of heat stress and drought during summer, especially for the Pannonian region [30,31]. In comparison with average measurements for our region in the period from 1981–2010, April and May of 2021 were much colder than normal [32], and the summer months of 2021 were relatively hot and dry. During maize vegetation, there was only 327.5 mm of rain, which was not distributed uniformly. The greatest precipitation deficit occurred during June 2021 (Figure 1).

During the hot summer months of June, July, and most of August (from maize stage V5 to stage R4), there was not sufficient humidity for plants, according to the hydrothermal coefficient (Table 1).

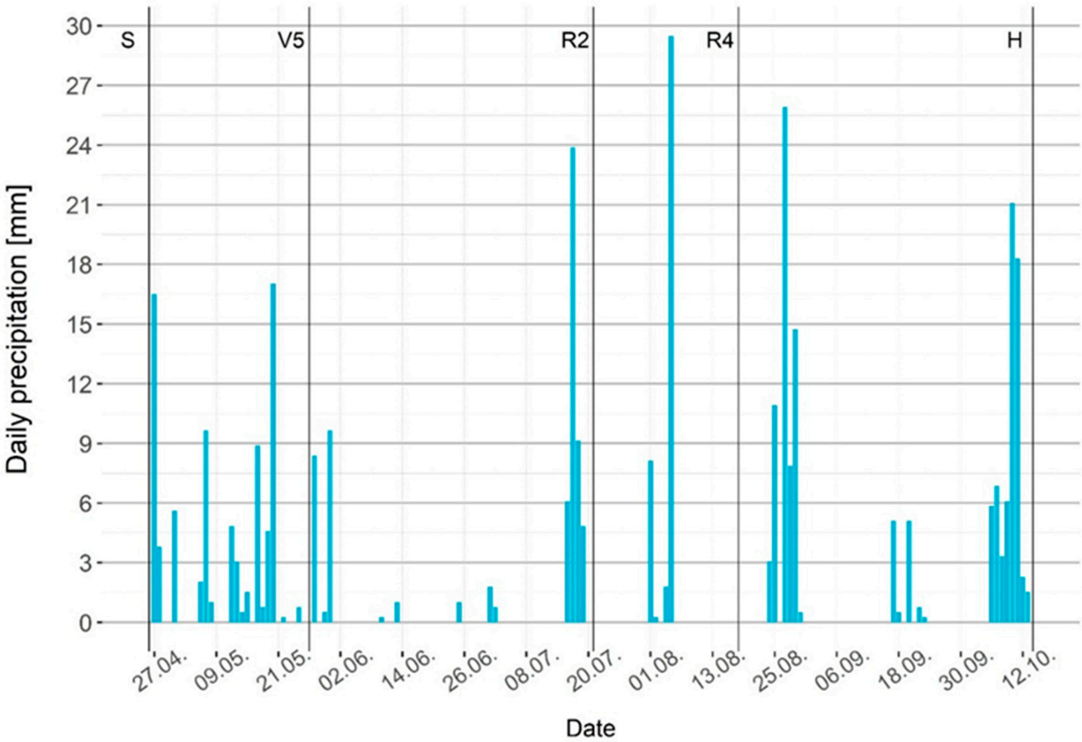

Figure 1. Daily precipitation for 2021 during maize vegetation. S—maize sowing date; V5—maize five leaves stage; R2—maize blister stage; R4—maize dough stage; H—maize harvest.

Table 1. Hydrothermal coefficient for 2021 during maize vegetation. S—maize sowing date; V5—maize five leaves stage; R2—maize blister stage; R4—maize dough stage; H—maize harvest.

Period	K
S–V5	1.8
V5–R2	0.54
R2–R4	0.57
R4–H	1.51

However, the intercropped system did seem to mediate these conditions in terms of microclimate changes. Generally, it had lower maximum and higher minimum temperature and humidity than the maize monoculture system (Figures 2 and 3), meaning there was less oscillation on daily basis, which can help plants adapt and resist stress conditions. There was no significant difference in daily temperature extremes between the monoculture and intercropped systems during the first month of maize growth, as this is when walnut only begins to develop foliage and thereby does not yet cause significant shading of the understory. However, significant differences were found in terms of both maximum and minimum daily temperatures during the period from the maize five leaves stage (V5) to the dough stage (R4), as well as minimum temperature from the dough stage (R4) until harvest (H). This was when the intercropped system had lower maximum temperatures and higher minimum temperatures, providing more stable conditions (Tukey's HSD, $p < 0.05$) (Figure 2). Regarding the daily relative humidity, the analysis of variance showed a statistically significant difference between the two systems during all maize growth stages, i.e., the whole vegetation. The intercropped system had higher maximum and minimum relative humidity, except during the first month of maize growth when the monoculture system had higher maximum humidity (Tukey's HSD, $p < 0.05$) (Figure 3). These positive changes in microclimate in the intercropped system with trees were mostly due to shading and wind reduction, which can buffer the temperature, increase air humidity, and result in reduced evapotranspiration [33]. Similar results have been obtained in other studies on tree-based systems across different regions [4,34–36].

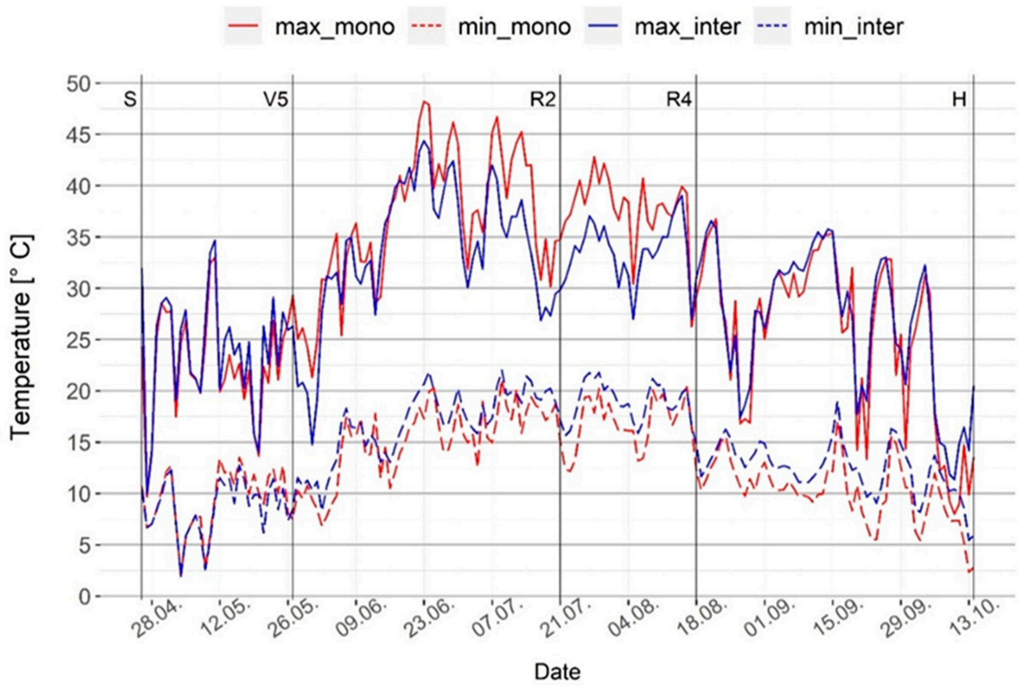

Figure 2. Daily temperature range (minimum and maximum) inside maize rows in the monoculture and intercropped systems. S—maize sowing date; V5—maize five leaves stage; R2—maize blister stage; R4—maize dough stage; H—maize harvest.

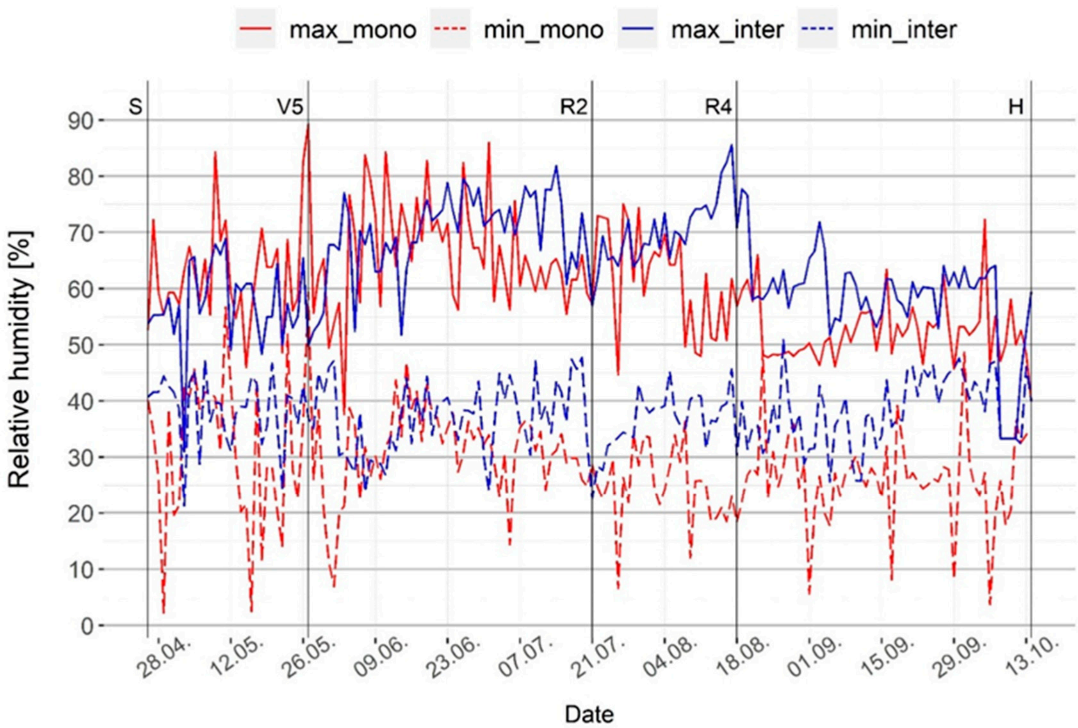

Figure 3. Daily humidity range (minimum and maximum) inside maize rows in the monoculture and intercropped systems. S—maize sowing date; V5—maize five leaves stage; R2—maize blister stage; R4—maize dough stage; H—maize harvest.

3.2. Soil Water Content

Initially, soil water content was similar in the three observed systems, as well as at the end of maize vegetation. In April, walnut trees have not yet produced foliage, and in October, when maize is harvested, walnut trees have already lost the majority of their leaves. Accordingly, walnut water demand during these periods is not high; therefore, soil water content is not affected by water uptake. The intercropped system conserved more water during the V5 stage than both the monoculture maize and the orchard, but later in vegetation, it had much less than the monoculture maize, especially in the deeper soil layers, which could be an indicator of the walnut water uptake pattern (Figure 4). Positive effects of trees on the microclimate in terms of decreased day temperatures, increased air humidity, and the lower transpiration rate of plants in shade could lead to greater conservation of soil water in intercropped systems. This outcome was found by Panozzo et al. [34] in their study conducted in Southern France—greater water availability was observed in the olive-wheat system than in the wheat monoculture system, and these differences were most pronounced during the last period of wheat vegetation (May and June). Even though we observed similar microclimate changes in our study (Figures 2 and 3) and there was more water in the intercropped system during late May (maize V5 stage) (Figure 4), the competition for water between the walnut trees and the maize increased significantly during dry summer months, which led to lower soil water content than in the monoculture maize system. These observations were not unexpected considering the precipitation deficit and high temperatures that occurred during this period, but also, in this period walnut consumed most of the water due to fruit expansion [37] and the peak of fine root production [38,39]. Simpson [9] also found that below-ground competition between trees and maize led to lower soil water content than in monoculture maize, even in shallow soil layers.

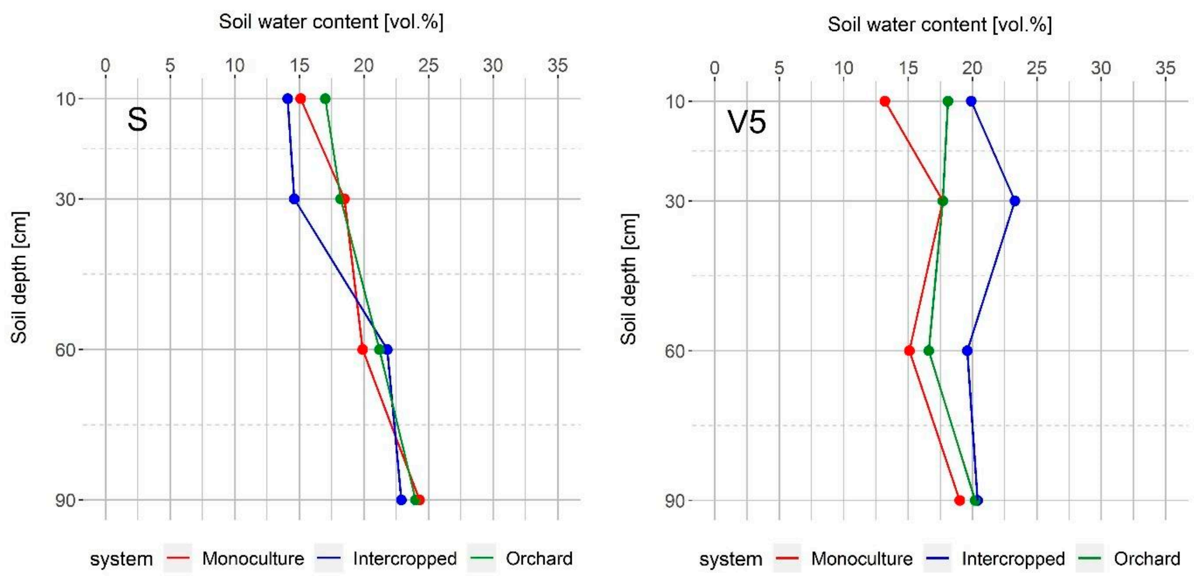

Figure 4. *Cont.*

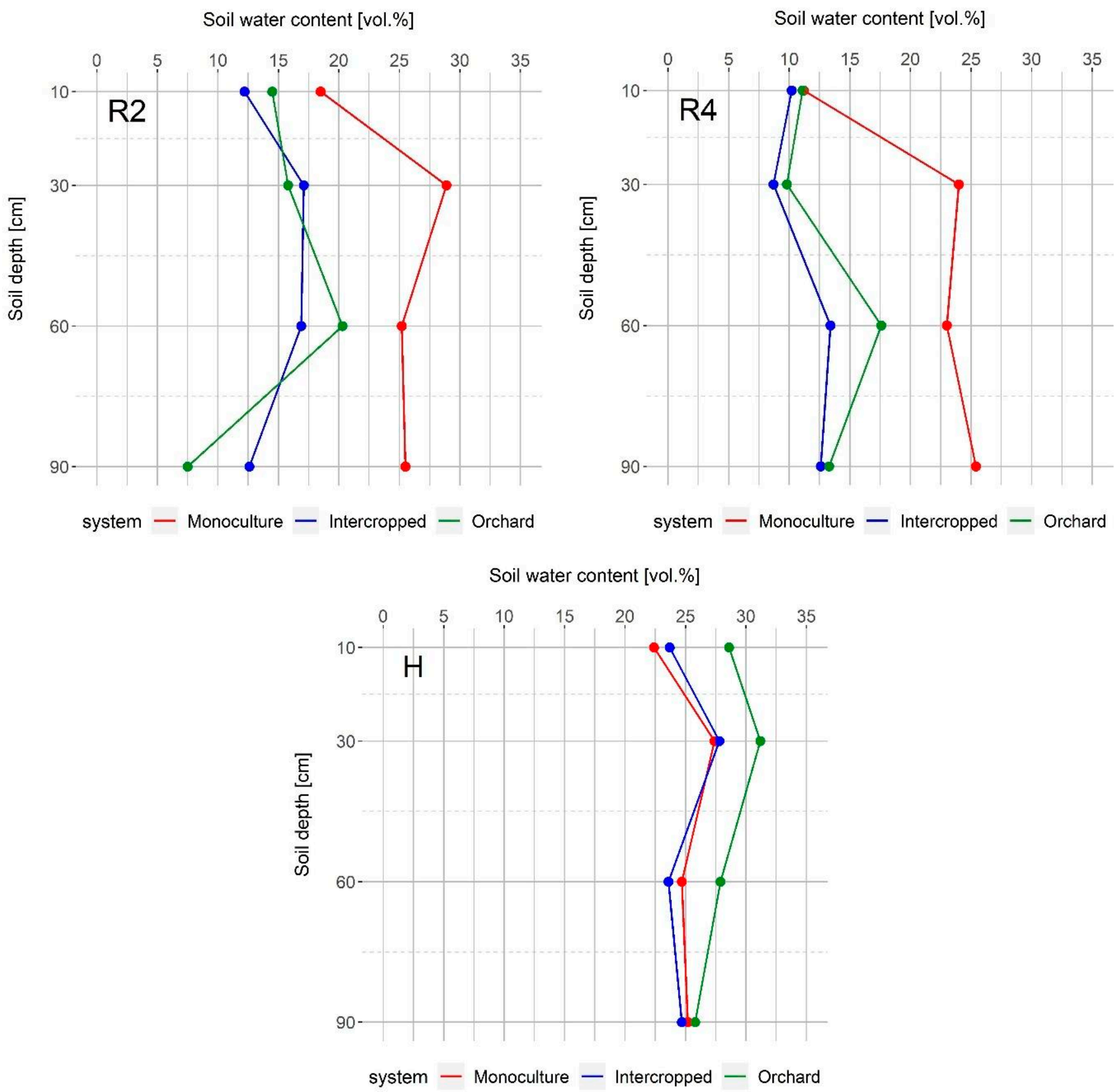

Figure 4. Soil volumetric water content in the monoculture and intercropped systems, and the walnut orchard during: S—maize sowing date; V5—five leaves stage; R2—blister stage; R4—dough stage; H—harvest. Data show average values for the 10-day recording period.

3.3. Soil Chemical Properties

The soil chemical properties showed that soil in the intercropped system did not differ significantly from the soil in the sole walnut orchard, except for higher potassium content in the sole orchard. Differences between the soil in the intercropped system and monoculture maize showed mostly in the pH and organic matter content, which were significantly higher for the intercropped system (Table 2). Many studies have confirmed the significant contribution of tree-based systems to soil carbon sequestration [40–43], which in turn contributes to greater carbon pools in the soil and greater aboveground biomass than in agricultural monoculture systems [44,45]. Organic carbon is a major component of soil organic matter, and it is found in greater content in tree-based systems than in monoculture crop systems due to the increased input of litter and roots, and the reduction of soil temperature through shading [46,47]. The lower OM content in intercropped systems compared to sole orchards could be due to the disturbance of the soil by tillage practices [48], although the difference in our case was not significant.

Table 2. Soil chemical properties during maize vegetation.

System	pH	OM [%]	P2O5 [mg kg^{-1}]	K2O [mg kg^{-1}]	N-min [mg kg^{-1}]
Monoculture maize	5.46 b	1.61 b	98.26 a	129.41 b	23.66 a
Intercropped	6.32 a	1.89 a	91.10 a	141.80 b	18.06 ab
Orchard	6.19 a	1.92 a	84.34 a	163.66 a	16.37 b

Different letters indicate statistically significant differences between systems (Tukey's HSD, $p < 0.05$).

3.4. Maize Growth and Leaf Greenness during Vegetation

Regarding growth traits measured during vegetation, statistically significant differences were observed in favor of intercropped maize compared to monoculture maize, despite observed competition for water. During whole vegetation, maize in the intercropped system was higher, and had a greater leaf area index and higher SPAD values than maize in the monoculture system. Initially, it also had higher aboveground biomass (until R4 stage) (Table 3). All of these were a sign of maize adapting to shaded conditions—plants grown in shade tend to grow higher and produce greater leaf area in order to reach more light [49–51]. Even though incoming photosynthetically active radiation is a major determinant of plants' dry matter production, photosynthetic efficiency is also driven by plant leaf area, leaf area density, and leaf area duration [52,53], which is why plants grown in mixed systems do not necessarily have reduced photosynthesis. Gillespie et al. [10] found no effect of tree shading on maize net photosynthesis, while Zhang et al. [54] found that net photosynthetic efficiencies on leaf level in mixed crops were even higher than in sole crops due to the increase in the proportion of diffuse radiation. Our earlier studies have shown that on the experimental site, solar radiation under the canopy during the summer months does not fall below 10,000 lux, which is sufficient for normal plant growth [55]. Higher aboveground biomass of intercropped maize correlates with increased height and leaf area; however, this comes at the cost of carbon invested in the stems [49]. It seems this could have been the case in our study—at the end of vegetation, when leaves senesced and began to fall apart, the monoculture maize had higher aboveground biomass due to more dry matter allocated to the stem (Table 3). Another case could be that the maize in the monoculture system prolonged carbon allocation in vegetative organs due to unfavorable microclimate conditions, instead of investing more carbon into grain filling.

Table 3. Maize traits measured during: S—maize sowing date; V5—five leaves stage; R2—blister stage; R4—dough stage; H—harvest.

	System	V5	R2	R4	H
Height [cm]	monoculture	22.9 b	181.8 b	206.4 b	180.0 b
	intercropped	36.0 a	220.1 a	229.8 a	223.0 a
Aboveground biomass [kg ha^{-1}]	monoculture	26.5 b	7191.3 b	13,856.1 a	21,918.1 a
	intercropped	36.0 a	10,589.4 a	16,838.3 a	17,768.4 b
LAI [m^2 m^{-2}]	monoculture	0.07 b	3.00 b	3.21 b	-
	intercropped	0.13 a	3.47 a	4.94 a	-
SPAD values	monoculture	31.19 b	40.47 b	49.44 b	-
	intercropped	33.68 a	57.06 a	55.45 a	-

Different letters indicate statistically significant differences between systems (Tukey's HSD, $p < 0.05$).

3.5. Yields, Yield Components, and LER

Tabolt et al. [56] argued that shading is crucial for crop yields in an intercropped system with trees. The shading effect on understory crops depends on many other factors. One of these is tree species, i.e., its crown structure. Reynolds et al. [8] reported that shading by poplar trees impacted maize performance to a greater extent than shading by silver maple trees, which was determined by the differences in height and canopy structure between these two tree species. Surprisingly, Rao et al. [57] found that maize yield was positively affected under the shade of Peltophorum, a slow-growing tree with a small canopy. The walnut trees' round, irregular, half-open crown fits the criteria of a good woody species for intercropped systems with crops [15]. Tree row orientation also plays an important role. Unless canopies converge and overlap, N–S row orientation casts less shade on the middle of the alley than E–W orientation, especially in higher latitudes. Under N–S orientation, the shadows from trees at noon, when most plant photosynthesis occurs, lay mostly under tree rows and not on crop rows [8,58,59]. Even though we observed that intercropped maize development was driven by reduced light availability, considering all of the above, we believe that the shading was not detrimental to the reduced maize yield in our study. Instead, significantly lower maize plant density in the intercropped system was the main determinant of significantly lower grain yield per total area (Table 4). In our previous studies in the same walnut orchard, we found that crop plant density was always lowered in comparison to the monoculture systems; wheat by 16%, barley by 13%, and buckwheat by 29% (unpublished data). Lower maize density, i.e., reduced germination in intercropped systems with walnut could be associated with walnut allelopathic properties, more precisely juglone excretion to the soil [60]. Juglone (5-hydroxy-1,4-naphthoquinone) is an organic compound found in all plant parts of the Juglandaceae family and is known to cause inhibition of germination and growth [16]. However, more research is needed to confirm the potential and extent of juglone build-up in the soil under walnut orchards. To gain more insightful information about the effect of trees on maize yield, we also calculated the yield per cropped area, i.e., excluding the area occupied by trees, but still accounting for lowered maize plant density. In this scenario, maize yield per cropped area was 96.61% of that in the monoculture system, which shows that besides less area for growing maize and despite fewer plants emerging, maize yield was not significantly impacted by walnut trees (Table 4).

Table 4. Maize yield (dry matter basis) and yield components.

	Monoculture Maize	Intercropped Maize
Density [plants ha^{-1}]	67,750 a	54,000 b
Grain yield per cropped area [kg ha^{-1}]	9448 a	9127 a
Grain yield per total area [kg ha^{-1}]	9448 a	6845 b
1000 kernel weight [g]	301.61 b	343.43 a
Harvest index	0.43 a	0.52 a

Different letters indicate statistically significant differences between systems (Tukey's HSD, $p < 0.05$).

Nevertheless, the reduction in the number of plants per area was probably compensated by increasing the productivity of individual plants [61,62], so intercropped maize achieved a higher harvest index and significantly greater 1000 kernel weight than monoculture maize (Table 4). Besides plant density, environmental factors should also be considered for observing these differences. Temperature thresholds for maize reproductive development are considerably lower than those for vegetative growth and are often exceeded for summer crops in our region. Biomass accumulation and transport capacity can be severely affected under such conditions, leading to a reduction in kernel number and weight [63]. Although the microclimate under tree rows can improve biomass remobilization towards grain [64], intercropped maize might also have preferentially began allocating assimilates to grains at the expense of total biomass due to limited water availability, i.e., competition with walnut trees. Similar observations have been previously reported for sorghum [65] and soybean [66]. This theory could explain our results for the maize plant aboveground biomass during vegetation, the 1000 kernel weight, as well as the improved harvest index. We found a 12% increase in the 1000 kernel weight of intercropped maize compared to monoculture maize. Similarly, Temani et al. [33] found that grain weights under olive orchards were increased by 17% for faba bean and 39% for wheat.

Walnut fruit yield amounted to a total of 1777 kg ha^{-1} in the intercropped system and 2997 kg ha^{-1} in the sole walnut orchard. This led to a walnut pLER of 0.59. The relatively low pLER of walnut in the intercropped system can not be ascribed to the competition with maize and is solely due to undefined differences between the two parts of the orchard. Namely, the orchard in this study had contrasting fruit yields between the first and last five rows of walnut trees since establishment, i.e., long before introducing intercrops. The first five tree rows always produced significantly less fruit yield than the last five, and the reason for intercropping crops between these first rows was to increase the total productivity of the area. Maize pLER was calculated on basis of total area (including the area occupied by trees), and amounted to 0.72. Together, these pLERs gave the intercropped system a high LER of 1.32, meaning it was 32% more productive per unit of land than cultivating these species separately. Some other studies, under different climates and designs, have also shown that tree-based intercropping systems with maize can achieve LER > 1 [67–70]. Our previous work [71] on simulating the productivity of intercropped systems using the Yield-SAFE model calibrated for our walnut orchard showed that, although intercropped maize could achieve surprisingly high yield while trees are young, by the time they reach year 13, maize pLER drops drastically and ranges from 0.18 to 0.55 depending on tree density scenario. However, by this time, walnut is in full fruit production maturity and its pLER could leverage a total LER towards LER > 1 (1.20 in the worst-case scenario with the highest tree density). Nevertheless, it would be expected that due to temporal complementarity in resource use between trees and crops, intercropping winter crops results in greater LER than intercropping summer crops. Under our experiments so far, we found that the best intercrops with walnut trees in terms of LER were as follows: winter barley—1.53 [18], perennial ryegrass—1.44 (unpublished data), maize—1.32, winter wheat—1.18 [72], buckwheat—1.05 [18].

3.6. Water Use, Water Productivity, and Water Equivalent Ratio

Complementarity in water use in intercropped systems with deciduous trees could be maintained either spacially [37,73]—by choosing deep-rooting trees with a long taproot and little or no lateral spreading [15], or temporally—by intercropping winter crops that can satisfy most of its water needs before the trees begin leafing and consume more water [74,75]. Such design and species selections could lead to maximum efficiency in water use for the intercropped system and maximize productivity.

The monoculture maize system in our experiment used the most water, i.e., it had the highest evapotranspiration of the three observed systems (Table 5). Considering the higher temperatures and lower humidity in this system, this is probably a result of a greater share of soil evaporation than in systems with trees [76–78]. The sole walnut orchard used the least water, which is probably only due to the combination of reduced soil evaporation and the transpiration of trees. Due to its higher yield and absence of competition for water with trees, monoculture maize had higher water productivity (also called water use efficiency—WUE) than maize in the intercropped system, although this difference was not statistically significant (Tukey's HSD, $p > 0.05$) (Table 5). Sole walnuts used less water than the intercropped system, and considering its much higher yield, it was also more productive per unit of water used. However, the intercropped system reached a WER of 1.31, which means that maize and walnuts grown together were 31% more efficient in using water than the monoculture system. The WER value followed closely the LER value, as has been seen in some other studies [25,79].

Table 5. Water use (WU [mm]), water productivity (WP [kg/ha/mm]), and water equivalent ratio (WER).

System	WU	WP	pWER	WER
Monoculture maize	272.75	40.3	-	-
Walnut orchard	244.75	12.2	-	-
Intercropped system; Maize Walnut	261.53	30.4 6.8	0.76 0.55	1.31

3.7. Nutrient Indices

Trees provide environmental services by reducing nutrient losses via a safety net, the uplift of deep soil nutrients, fixation of N_2, and changing morphological and chemical processes at the rhizosphere [7], which can then indirectly benefit the nutrient uptake of crops in agroforestry systems. Studies have found that crops in an intercropped system with trees gained higher nutrient content in biomass and/or grain in comparison with monoculture systems [12,59,74,80,81]. In our previous study, we also found that barley in the intercropped system had significantly higher N, P, and K grain content [82]. However, we observed the contrary with intercropped maize (Table 6).

Table 6. Grain nutrient contents and nutrient indices; NP, PP, KP—grain productivity [kg ha^{-1} [kg soil nutrient ha^{-1}]$^{-1}$], NUE, PUE, KUE—nutrient use efficiencies [kg ha^{-1} [kg total accumulated nutrient ha^{-1}]$^{-1}$], NRI, PRI, KRI—nutrient recovery indices [kg grain accumulated nutrient ha^{-1} [kg soil nutrient ha^{-1}]$^{-1}$].

	Monoculture Maize	Intercropped Maize
N [%]	1.38 a	1.36 b
P [%]	0.25 a	0.25 a
K [%]	0.35 a	0.34 b
NP	43.21 a	54.68 a
PP	10.41 a	10.84 a
KP	7.90 a	6.97 a
NUE	25.33 a	29.01 a
PUE	160.75 a	176.91 a
KUE	47.44 b	57.98 a
NRI	0.88 a	0.70 a
PRI	0.03 a	0.03 a
KRI	0.03 a	0.02 a

Different letters indicate statistically significant differences between systems (Tukey's HSD, $p < 0.05$).

Gillespie [83] stated that greater competition between trees and crops in agroforestry systems is most likely to occur for nitrogen as nitrate and potassium. We found that monoculture maize had higher grain nitrogen and potassium content (N% and K%) than intercropped maize (Table 6). Even though intercropped maize had higher nitrogen, phosphorus, and potassium use efficiencies (NUE, PUE, KUE), meaning that it produced more dry grain mass per kg of those nutrients accumulated (Table 6), the difference was significant only for potassium. Our results are comparable with those observed by Ciampitti and Vyn [84] and Ciampitti et al. [85]—nitrogen and phosphorus use efficiency (denoted as NIE and PIE) increased exponentially as the grain concentration of those nutrients declined. Higher nutrient use efficiencies in the intercropped system in this study could be related to decreased plant density, as there is less intra-species competition (Table 3). Furthermore, intercropped maize also produced slightly higher grain yield per available nitrogen and phosphorus (NP and PP), which could be related to lower nitrogen and phosphorus content in the soil [24]. Schmidt et al. [27] examined grain nutrient productivity (denoted as NRE—nutrient response efficiency) in crops in intercropped systems across three different sites, i.e., different soil types. They reported that nutrient productivities were comparable between crops in monoculture and intercropped systems, due to similar yields and nutrient availability in the soil. Similarly to our results, they did not observe any KP advantage during their study but found a higher NP of intercrops on gleyic cambisol. The nutrient recovery indices (NRI, PRI, KRI) showed no significant difference for maize between the monoculture and intercropped systems, indicating that the ability of maize to partition nutrients in grain was not affected by its possible competition with walnut trees.

4. Conclusions

Maintaining agricultural production at a high level while ensuring sustainability to face climate change challenges is a high priority around the globe. The role of trees in modifying microclimate conditions on agricultural land can be significant in mitigating heat stress. Our study showed that combining walnut orchards with maize in temperate regions has a lot of potential for sustaining the high land and water productivity of the system while having the benefit of improved microclimate conditions for crops. Land and water equivalent ratios of 1.32 and 1.31, respectively, showed an advantage for the walnut-maize intercropped system, meaning that for achieving equivalent yields in monoculture systems, these species would need both more land and more water. Despite the anticipated negative effects of shade on C4 crops such as maize, we found this was not a limiting factor for maize productivity in the system intercropped with walnut. Moreover, the maize seemed to proficiently adapt its growth to these conditions by increasing its aboveground growth. It is important to note here the importance of tree row orientation, as E–W orientation can limit light availability for intercrops to a greater extent than N–S orientation. Belowground, we did observe possible water competition with trees during the walnut fruit expansion stage, but the main limiting factor for decreased maize yield per unit of the total area was reduced germination. Many studies have reported the negative effects of walnut juglone excretion on plants grown nearby, and this may have been the case in our 14-year-old orchard. However, more research is needed to evaluate the extent of this allelopathic potential regarding tree age, soil type, etc. Nevertheless, the reduction in the number of plants per area was compensated by the increased productivity of individual plants, so intercropped maize achieved a higher harvest index and significantly greater 1000 kernel weight than monoculture maize. Furthermore, we did not find an increase in grain nutrient content as observed in previous studies and seen in the literature. On the contrary, monoculture maize achieved higher nitrogen and potassium content. No significant differences were found in terms of maize grain productivity per unit of soil nutrients or grain nutrient recovery. However, intercropped maize did produce more grain mass per unit of accumulated nitrogen and potassium. Further research should focus on providing insights into the trade-off between radiation decrease and microclimate improvements in intercropped systems with summer crops. Also, potential allelopathic associations in mature walnut orchards should be assessed.

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Naslov izvornog znanstvenog rada broj 1: Modelling the yield and profitability of intercropped walnut systems in Croatia

Prošireni sažetak:

Primijećeni rast interesa za voćarstvo u Hrvatskoj, osobito za uzgoj oraha, predstavlja dobru priliku za integraciju konsocijacijskih sustava kao načina intenziviranja poljoprivredne proizvodnje, ali i kao izvora financijskih dobiti u prvim godinama od podizanja nasada dok voćnjak ne dosegne rodnu zrelost i postane profitabilan. Ipak, sve agronomske i ekonomske prednosti ovise o brojnim faktorima koje je teško predvidjeti "napamet". Iz tog razloga, razvijeni su matematički modeli koji u obzir uzimaju razne parametre planiranog sustava, kao što su klimatski uvjeti, svojstva tla i odabranih biljnih vrsta te način upravljanja sustavom, kako bi predvidjeli moguće prinose i isplativost. Očekivani prinosi i isplativost konsocijacijskih sustava u ovom istraživanju procijenjeni su korištenjem biofizičkog simulacijskog modela Yield-SAFE za određivanje rasta i prinosa usjeva i drveća u pojedinačnim sustavima te u konsocijaciji, a ekonomski model Farm-SAFE korišten je za procjenu dugoročne isplativosti promatranih sustava. Model je postavljen za lokaciju u Đakovu, s dnevnim vremenskim klimatskim podacima izvedenim iz CliPick modela, koji su validirani usporedbom njegovih simuliranih podataka sa zabilježenim podacima s lokalne meteorološke postaje. Parametrizacija i kalibracija Yield-SAFE modela detaljno je objašnjena u publikacijama van der Werf i sur. (2007) i Graves i sur. (2010). Početna parametarizacija temeljena je na podacima dostupnim iz publikacija Hrvatskog statističkog ljetopisa te osobne komunikacije s poljoprivrednicima, a model je prije svega kalibriran prema poznatim prinosima ratarskih kultura na oranicama bez drveća. Najbolje poklapanje ("best fit") modela s promatranim, odnosno zabilježenim podacima dobiveno je mijenjanjem parametara za količinu transpirirane vode za usjeve i orah, žetvene indekse i dan sjetve. Vrijednosti ovih parametara mijenjane su unutar prihvatljivih raspona određenih literaturom i iskustvima poljoprivrednih proizvođača.. Voćnjak oraha i konsocijacijski sustavi ratarskih kultura simulirani su s tri scenarija gustoće stabala; 170, 135 i 100 stabala ha^{-1}, kako bi se utvrdila optimalna kombinacija intenziviranja proizvodnje i povećanja financijske dobiti. Analiza isplativosti temeljila se na izračunu vrijednosti godišnjih neto marži po hektaru za svaki sustav i svaki scenarij gustoće drveća, a kumulativne neto marže tijekom simulirane rotacije izračunate su zbrajanjem godišnjih vrijednosti. Biofizičkim modelom predviđen je trend pada prinosa ratarskih usjeva tijekom simuliranog perioda, u svim scenarijima gustoće stabala. Očekivano, najveći pad prinosa

dogodio se pri najvećoj gustoći stabala od 170 stabala ha^{-1}. Ipak, svi relativni prinosi usjeva bili su visoki tijekom prvih 7 godina, osobito za kukuruz. Iako se u ovakvim sustavima očekuje veća produktivnost ozimih kultura, nego jarih, isti mogu vrlo uspješno konkurirati za resurse dok drveće ne dosegne određeni nadzemni i podzemni rast, što omogućava ostvarenje punog prinosotvornog potencijala. Ova teorija potvrđena je i rezultatima simulacije prinosa oraha koji su pokazali da bi ratarske kulture u početku smanjile godišnju proizvodnju plodova oraha u konsocijacijskim sustavima. Ipak, model je pokazao i da s vremenom orah postaje apsolutno dominantnija vrsta u konsocijacijskim sustavima sa sva tri simulirana scenarija, te da usjevi nakon 13. godine više nemaju utjecaj na godišnje prinose oraha. Predviđeno je i da bi usjevi u konsocijacijskim sustavima do 20. godine postali i veći od onih u voćnjacima bez ratarskih usjeva, međutim ta razlika nije bila statistički značajna. Nadalje, analiza produktivnosti pokazala je da su simulirani konsocijacijski sustavi bili produktivniji od odvojene ratarske proizvodnje i proizvodnje oraha, za sve scenarije gustoće stabala. Financijska analiza pokazala je da je obradivi sustav ratarskih kultura bez drveća davao pozitivne i relativno dosljedne prihode tijekom 20 godina. Zbog visokih početnih troškova podizanja nasada oraha, konsocijacijski sustavi i voćnjaci oraha ostvarili su značajne gubitke tijekom prvih nekoliko godina, koji su nadoknađeni tek kada je orah počeo davati značajnije prinose. Model je predvidio da bi usjevi povećali isplativost konsocijacijskih sustava tijekom prvih 6 godina starosti oraha, međutim, nastavak usijavanja nakon tog razdoblja rezultirao je financijskim gubicima jer usjevi nisu mogli postići zadovoljavajuće prinose i prihode. U praksi, čim bi proizvodnja usjeva postala neprofitna, poljoprivrednik bi prestao s usijavanjem. Takvi scenariji s prekinutim usijavanjem u 7. godini rezultirali su većom neto maržom nakon 20 godina, u odnosu na voćnjake oraha bez usjeva i za sve tri gustoće, što je pokazalo da je praksa usijavanja ratarskih kultura u voćnjake oraha isplativa opcija za prijelaz s ratarstva na proizvodnju oraha. Međutim, ostaje sporno je li ova razlika u financijskoj dobiti dovoljna da bi se poljoprivredni proizvođači odlučili na praksu usijavanja.

Ključne riječi: bio-ekonomski model, konsocijacija, usijavanje, orah, voćnjak

Naslov izvornog znanstvenog rada broj 2: Land and Water Productivity in Intercropped Systems of Walnut—Buckwheat and Walnut–Barley: A Case Study

Prošireni sažetak:

Pozitivan utjecaj drveća na mikroklimu u konsocijacijskim sustavima, ponajprije na smanjenje evaporacije, odnosno gubitka vode iz tla, osnova je očekivane prednosti u korištenju vode u ovim sustavima, u odnosu na pojedinačno uzgajane drvenaste i ratarske kulture. Iako usijavanje ratarskih kultura u voćnjake predstavlja ekološki održivo intenziviranje poljoprivredne proizvodnje, uvjet je komplementarnost odabranih vrsta u dijeljenju resursa. Vrsta drveća, starost i gustoća sadnje značajno utječu na količinu sjene i kompeticiju za podzemne resurse, tako da različite kombinacije ovih čimbenika daju vrlo različite rezultate. Komplementarnost u korištenju dostupnih resursa, ponajprije vode, temelji se na optimalnim prostorno-vremenskim interakcijama između biljaka u konsocijacijskim sustavima. Prostorna komplementarnost postiže se odabirom vrsta drveća koje ima duboko korijenje s malo bočnog grananja, praksom orezivanja korijenja ili usijavanjem vrlo kompetitivnih ratarskih kultura u prvim godinama, koje će potaknuti jači vertikalni nego horizontalni rast korijenja drveća. Time se postiže usvajanje vode iz različitih horizonata tla, što smanjuje kompeticijske odnose i povećava produktivnost. Vremenska komplementarnost postiže se odabirom ozimih ratarskih usjeva koji većinu svog rasta i razvoja postižu u periodu kada drveće nije u fazi aktivnog rasta i razvoja plodova kada najintenzivnije troši vodu. Cilj ovog istraživanja bio je ispitati produktivnost konsocijacijskih sustava s orahom u odnosu na iskorištenu površinu i vodu, a korištene su dvije ratarske kulture; heljda – jari usjev s visokim potrebama za vodom i ječam – ozimi usjev s relativno niskim potrebama za vodom. Ove kombinacije sustava promatrane su na dvije lokacije, odnosno u dva različita voćnjaka – mlađem, sa širim razmakom među redovima stabala te u starijem, s užim sadnim razmakom. Osim prinosa i produktivnosti, određeni su i hidrometeorološki uvjeti, a evapotranspiracija u promatranim sustavima određena je korištenjem jednostavne vodne bilance. Produktivnost vode određena je iz odnosa prinosa i evapotranspiracije za svaki usjev posebno, a ukupna učinkovitost usvajanja vode konsocijacijskih sustava određena je u starijem, zrelom voćnjaku koji daje prinose. Rezultati su pokazali smanjenje prinosa i produktivnosti vode usjeva u konsocijaciji, u odnosu na kontrolne parcele bez drveća. Izuzetak je bila heljda u mlađem voćnjaku, gdje je iznenađujuće ostvarila najveći prinos i produktivnost po jedinici usvojene

vode. Općenito, na toj lokaciji zabilježeni su povoljniji klimatski i hidrološki uvjeti što je smanjilo kompeticiju za vodu s drvećem, a zasjena uzrokovana manjim krošnjama drveća nije imala značajan negativni utjecaj. S druge strane, iako su stabla oraha u starijem voćnjaku značajnije utjecala na smanjenje evapotranspiracije, kompeticija s drvećem oraha ograničila je dostupnost vode za heljdu, a na smanjenje prinosa utjecala je i značajnija zasjena. Ovaj sustav ostvario je prosječne vrijednosti LER 1,05 i WER 1,12, što ipak ukazuje na prednost u odnosu na pojedinačne sustave heljde i oraha. Što se tiče ječma, zabilježeno je smanjenje relativnih prinosa na obje lokacije. Ipak, sustav ječma i oraha u starijem voćnjaku bio je čak 53% produktivniji po jedinici površine i 83% produktivniji po jedinici usvojene vode nego uzgoj oraha i ječma zasebno, ali također i 48% i 70% produktivniji po jedinici površine i usvojene vode od sustava orah–heljda. Vrijednosti evapotranspirirane vode bile su konstantno veće u konsocijacijskim sustavima s mlađim nego starijim stablima oraha, a te se razlike djelomično mogu objasniti razlikama u količini oborina i drugim klimatskim uvjetima na promatranim lokacijama. Također, u sustavu sa starijim orahom zabilježeno je i najveće smanjenje evapotranspiracije u odnosu na promatrane kontrolne parcele usjeva bez drveća. Rezultati ovog istraživanja ukazuju na pozitivne učinke drveća na mikroklimu, povećanje produktivnosti po jedinici površine i učinkovitosti korištenja vode, ali također naglašavaju važnost odabira vrsta i dizajna sustava.

Ključne riječi: konsocijacija, orah, produktivnost, učinkovitost usvajanja vode

Naslov izvornog znanstvenog rada broj 3: Ecological and Agronomic Benefits of Intercropping Maize in a Walnut Orchard—A Case Study

Prošireni sažetak:

Trend porasta temperatura zbog klimatskih promjena već je dobro evidentiran i brojne klimatske projekcije budućnosti pokazuju da je nastavak ovog trenda neizbježan. Općenito, mnoge će se regije tijekom ljeta suočiti s toplijim i sušnijim uvjetima, što ukazuje na visok rizik za poljoprivrednu proizvodnju. Kukuruz, jedan od najvažnijih usjeva, mogao bi biti posebno osjetljiv na ovakve promjene. Osim selekcije hibrida otpornijih na toplinski stres, prilagodba uzgoja kukuruza morat će se nositi ne samo s povišenim prosječnim temperaturama, već i sa sve većom učestalošću ekstremnih klimatskih uvjeta. Veliki potencijal za ublažavanje ovih uvjeta pokazao se uvođenjem stabala na tradicionalne ratarske površine, odnosno uspostavljanjem konsocijacijskih sustava. Drveće u takvim sustavima modificira mikroklimu smanjujući intenzitet sunčevog zračenja, temperaturne oscilacije i jačinu vjetra te povećavajući relativnu vlažnost zraka. Ove promjene dovode do smanjenja evapotranspiracije i poboljšanja korištenja vode za takve sustave, te u konačnici do stabilnijih uvjeta za usjeve koji se uzgajaju ispod drveća. Nadalje, jedan od važnijih potencijala ovih sustava je i smanjenje ovisnosti o gnojidbi, putem boljeg iskorištavanja hranivih tvari u tlu. Drveće može pozitivno utjecati na usvajanje hraniva usjeva smanjenjem gubitaka, odnosno ispiranja hraniva putem tzv. sigurnosne mreže, podizanjem hranivih tvari iz dubljih slojeva tla, te promjenama u kemijskim procesima u rizosferi djelovanjem korijena. Pod navedenim pretpostavkama, ovo istraživanje imalo je za cilj kvantificirati potencijalne mikroklimatske promjene u konsocijacijskim sustavima i procijeniti mogu li iste pomoći u rastu i razvoju kukuruza, unatoč očekivanoj konkurenciji za resurse s orasima. Provedeno je mjerenje i analiza (i) parametara mikroklime; (ii) vlažnosti tla; (iii) fenologije kukuruza, rasta, prinosa i usvajanja makrohraniva (N, P i K), i (iv) ukupne produktivnosti sustava po jedinici površine i usvojene vode. Produktivnost vode određena je iz odnosa prinosa i evapotranspiracije, a indeksi učinkovitosti usvajanja hraniva kukuruza određeni su s obzirom na količinu hraniva dostupnog u tlu i usvojenog tijekom vegetacije. Ukupna produktivnost sustava po jedinici površine i usvojene vode izražena je pomoću LER i WER vrijednosti. Rezultati su pokazali da su stabla oraha imala pozitivan utjecaj na mikroklimatske uvjete u sustavu. Naime, u odnosu na kontrolnu parcelu bez drveća, u konsocijacijskom sustavu su utvrđene niže vrijednosti maksimalne

temperature zraka, a više vrijednosti minimalnih dnevnih temperatura, što znači da su osigurani stabilniji temperaturni uvjeti smanjenjem oscilacija na dnevnoj bazi. Također, prisutnost drveća utjecala je i na povećanje relativne vlažnosti zraka unutar redova kukuruza u konsocijacijskom sustavu. Ove pozitivne promjene bile su osobito izražene tijekom vrućih ljetnih mjeseci obilježenih manjkom oborina. Utvrđeno smanjenje prinosa kukuruza od 30% po ukupnoj površini u konsocijaciji s orahom bilo je rezultat značajno smanjene gustoće biljaka, odnosno klijavosti sjemena, što bi mogao biti učinak specifičan za orah zbog izlučivanja juglona. Ipak, smanjenje broja biljaka vjerojatno je kompenzirano povećanjem produktivnosti pojedinačnih, tako da je kukuruz u konsocijaciji postigao veći žetveni indeks i značajno veću masu 1000 zrna od kukuruza na kontrolnoj parceli bez drveća. Nisu pronađene značajne razlike između kukuruza uzgajanog sa i bez prisutnosti drveća u produktivnosti s obzirom na količinu hraniva dostupnih u tlu ili usvojenih tijekom vegetacije, kao ni u učinkovitosti mobilizacije hraniva u zrno, za sva tri promatrana makroelementa (N, P i K). Na razini sustava, uočena je prednost konsocijacijskog sustava oraha i kukuruza u usporedbi s pripadajućim pojedinačnim sustavima ove dvije kulture – LER i WER vrijednosti pokazale su da bi za postizanje istih prinosa kao u konsocijacijskom sustavu, orahu i kukuruzu koji se uzgajaju odvojeno bila potrebna 32% veća površina i 31% više vode. Ovo istraživanje utvrdilo je značajne prednosti u kombiniranju uzgoja oraha i kukuruza u odnosu na pojedinačni uzgoj, međutim, potrebna su detaljnija istraživanja rizosfere u sustavima s orahom zbog njegovih potencijalnih alelopatskih učinaka.

Ključne riječi: konsocijacija, orah, kukuruz, produktivnost, učinkovitost usvajanja vode, učinkovitost usvajanja makrohraniva

SAŽETAK

Potencijalne prednosti za usjeve u konsocijacijskim sustavima uglavnom se temelje na sposobnosti stabala da osiguraju povoljne mikroklimatske uvjete i time poboljšaju korištenje vode. Također, postoji i potencijal za komplementarni učinak drveća na povećanje dostupnosti hraniva putem raznih mehanizama. Ipak, smanjenje prinosa usjeva u konsocijacijskim sustavima očekivano je i opravdano zbog smanjenja površine na koju su usijani. Očekivana produktivnost i profitabilnost konsocijacijskih sustava može se predvidjeti korištenjem simulacijskih modela, što je i bio prvi cilj ovog istraživanja. Naime, korišteni su Yield-SAFE i Farm-SAFE modeli, razvijeni posebno za konsocijacijske sustave s drvećem, kako bi se odredile mogućnosti usijavanja ratarskih kultura (uljana repica, ječam, kukuruz) u voćnjak oraha u budućim klimatskim uvjetima naše regije. Nadalje, ovo istraživanje imalo je za cilj istražiti prinose i produktivnost vode usjeva u voćnjacima oraha različitog dizajna i starosti, kako bi se utvrdili učinci kontrastnih svojstava sustava na jari usjev (heljda) i ozimi usjev (ječam). Na kraju, treći dio ovog istraživanja detaljnije je fokusiran na mikroklimu i rast, komponente prinosa te korištenje vode i hranivih tvari kukuruza u konsocijacijskom sustavu s orahom. U prvom dijelu ovog istraživanja simulirana su tri sustava (ratarske kulture bez stabala, konsocijacijski sustavi i voćnjak oraha) za razdoblje od 20 godina. Konsocijacijski sustavi i voćnjak simulirani su u tri scenarija gustoće stabala; 170, 135 i 100 stabala po hektaru. Produktivnost konsocijacijskih sustava procijenjena je pomoću LER-a (Land Equivalent Ratio), a profitabilnost je određena izračunom godišnjih neto marži po hektaru za svaki sustav i svaki scenarij. Kumulativne neto marže tijekom perioda simuliranih rotacija izračunate su zbrajanjem godišnjih NPV (Net Present Values) vrijednosti. Nadalje, korištenje vode na pokusnim lokacijama određeno je za svaki sustav jednostavnom jednadžbom bilance vode koja predstavlja evapotranspiraciju, a zatim je korištena za procjenu produktivnosti vodne oraha i usjeva. Ukupna učinkovitost usvajanja vode konsocijacijskih sustava procijenjena je korištenjem WER-a (Water Equivalent Ratio). Nadalje, mjerene su dnevne maksimalne i minimalne vrijednosti temperature i relativne vlažnosti zraka kako bi se analizirale razlike u mikroklimatskim uvjetima između kontrolne parcele kukuruza i konsocijacijskog sustava. Također, provedena je detaljnija analiza komponenti rasta i prinosa kukuruza koja je uključivala mjerenja visine, biomase, LAI, SPAD, gustoće biljaka, žetvenog indeksa i mase 1000 zrna. Dodatno, korišteni su različiti indeksi za određivanje učinkovitosti

korištenja N, P i K kukuruza uzgajanog pojedinačno i u konsocijaciji s orasima. Model Yield-SAFE predvidio je da će, osim visokih prinosa kukuruza u prvih nekoliko godina, prinosi usjeva u konsocijacijskim sustavima s orasima biti niži od onih na kontrolnoj parceli bez drveća, te da bi usjevi mogli ograničiti produktivnost stabala oraha. Ipak, kombinirani relativni prinosi rezultirali su s LER > 1 za sva tri scenarija gustoće, što znači da su konsocijacijski sustavi bili produktivniji od odvojenog uzgoja oraha i usjeva, čak i nakon 20 godina. Uzgoj usjeva tijekom prvih šest godina pružio je i financijsku korist u nadoknadi visokih troškova osnivanja voćnjaka osiguravanjem dodatnog prihoda. Ovaj scenarij usijavanja tijekom šest godina i zatim održavanja samo voćnjaka pokazao se najisplativijim tijekom simuliranog razdoblja od 20 godina. Analiza je također pokazala da je gustoća od 170 stabala ha^{-1} rezultirala najvišim neto maržama za svaku od 20 simuliranih godina. Značajan utjecaj na mikroklimu zabilježen je u starijem voćnjaku, što je rezultat većih stabala oraha i užih razmaka sadnje. U usporedbi s parcelama bez drveća, evapotranspiracija je bila niža u konsocijacijskim sustavima tijekom sve tri promatrane godine. Mjerenja dnevnih temperatura i relativne vlažnosti zraka pokazala su ublažavanje ekstremnih uvjeta unutar redova kukuruza u konsocijacijskom sustavu, a taj je učinak bio najizraženiji tijekom toplih i suhih ljetnih mjeseci. Bez obzira na smanjenje prinosa usjeva u konsocijaciji s orahom, ovi sustavi postigli su veću produktivnost po jedinici površine od zasebno uzgajanih kultura. LER vrijednosti bile su 1,05, 1,32 i 1,53 za sustave s heljdom, kukuruzom i ječmom. Zbog konkurencije sa stablima oraha produktivnost usjeva po jedinici utrošene vode bila je niža u konsocijaciji nego u kontrolnim parcelama. Međutim, uzimajući u obzir cijeli sustav, postojala je prednost u učinkovitosti usvajanja vode; konsocijacijski sustavi postigli su WER vrijednosti od 1,12, 1,31, i 1,83 za sustave s heljdom, kukuruzom i ječmom. Iako su u konsocijaciji oraha i kukuruza zabilježene pozitivne mikroklimatske promjene, uočen je i negativan utjecaj stabala oraha na klijavost kukuruza, što je rezultiralo značajno manjim prinosom po ukupnoj površini u odnosu na prinos kukuruza na kontrolnoj parceli. Ipak, smanjenje broja isklijanih biljaka nadoknađeno je povećanjem produktivnosti pojedinačnih biljaka, pa je kukuruz u konsocijaciji ostvario veći žetveni indeks i značajno veću masu 1000 zrna. Nisu pronađene značajne razlike između promatranih sustava kukuruza u produktivnosti po jedinici raspoloživih hraniva u tlu, niti u učinkovitosti mobilizacije dostupnih hraniva u zrno. Ipak, kukuruz u konsocijaciji dao je veći prinos zrna po jedinici apsorbiranog dušika i kalija. Ovo istraživanje pokazalo je da konsocijacija ratarskih kultura i oraha može biti održiva mjera intenziviranja poljoprivredne proizvodnje ili isplativ način prelaska s ratarske na voćarsku proizvodnju. Međutim, ukupna produktivnost te ekološka i ekonomska održivost mogu uvelike ovisiti o odabiru vrsta i dizajnu sustava.

SUMMARY

Potential advantages for crops in intercropped systems with trees are based mostly on the tree's ability to provide beneficial microclimatic conditions in these systems and thereby improve the utilization of water. Also, there is a potential for the complimentary belowground effect of trees on improving nutrient availability via different mechanisms. Nevertheless, the reduction of intercrop yields is expected and justified due to the reduced crop area. The anticipated productivity and profitability of intercropped systems may be predicted using simulation models, which was the first aim of this study. Namely, we used Yield-SAFE and Farm-SAFE models developed specifically for intercropped systems with trees, to determine the possibilities of intercropping three common crops (rapeseed, barley, and grain maize) in the walnut orchard, under future climate conditions of our region. Secondly, this study aimed to investigate the yields and water productivity of crops intercropped in walnut orchards of different designs and maturity, to determine the effects of contrasting system properties on summer crop (buckwheat) and winter crop (barley). Lastly, the third part of this study focused more in-depth on the microclimate and growth, yield parameters, and water and nutrient use of intercropped grain maize. For the first part of this study, three systems (arable crop without trees, intercropped system, and walnut orchard) were simulated for a period of 20 years. Intercropped system and orchard were simulated in three tree density scenarios; 170, 135, and 100 trees per hectare. The productivity of intercropped system was evaluated using LER (Land Equivalent Ratio) and profitability was determined by deriving annual net margins per hectare for each system and each scenario. Cumulative net margins over the assumed rotation were calculated by adding up annual NPVs (Net Present Values). Secondly, the water use on our experimental plots was determined for each system by a simple water balance equation which represents the evapotranspiration, and was then used for the estimation of water productivity of walnut and crops. Overall water use efficiencies of intercropped systems were evaluated using WER (Water Equivalent Ratio). Lastly, daily maximum and minimum values of temperature and relative humidity were measured to analyze differences in microclimatic conditions between monoculture maize field and intercropped system. Further, a more detailed analysis of growth and yield components of grain maize included measurements of height, biomass, LAI, SPAD, density, harvest index, and 1000 kernel weight. Additionally, different indices were used to determine N, P, and K use efficiencies of grain maize in

monoculture and intercropped system with walnuts. The Yield-SAFE model predicted that, besides high maize yields in the first few years, crop yields in the intercropped system with walnuts would be lower than those in monoculture, and that crops could limit the productivity of walnut trees. Still, combined relative yields led to LER > 1 for all three density scenarios, which means these intercropped systems were more productive than growing walnuts and crops separately, even after 20 years. Intercropping during the first six years also provided a financial benefit in offsetting the high costs of orchard establishment by providing additional income. This scenario of intercropping for only six years and then maintaining a pure orchard proved to be the most profitable during the simulated period of 20 years. The analysis also showed that a density of 170 trees ha^{-1} resulted in the highest net margins for each of the 20 simulated years. A significant impact on the microclimate was recorded in the older orchard, which is the result of larger walnut trees and narrower planting distances. In comparison to monoculture plots without trees, evapotranspiration was lower in intercropped systems, during all three observed years. Measurements of daily temperature and relative air humidity showed mitigation of extreme conditions within the maize rows in the intercropped system, and this effect was most significantly expressed during the hot and dry summer months. Regardless of the crop yield reductions in the intercropped walnut orchard, these systems achieved higher productivity per unit area than separately grown walnuts and crops. LER values were 1.05, 1.32, and 1.53 for the systems with buckwheat, maize, and barley, respectively. Due to competition with walnut trees, crops productivity per unit of used water was lower in the intercropped system than in the control monoculture plots. However, taking into account the whole system, there was an advantage in the efficiency of water use; intercropped systems achieved WER values of 1.12, 1.31, and 1.83 for systems with buckwheat, maize, and barley, respectively. Although positive microclimatic changes have been noted in intercropped walnut-maize system, there was a negative effect of walnut trees on maize germination, which resulted in a significantly lower yield per total area compared to monoculture maize. Nevertheless, the decrease in the number of plants was compensated by the increase in the productivity of individual plants, so the intercropped maize achieved a higher harvest index and a significantly higher 1000 kernel weight. No significant differences were found between the maize systems in productivity per unit of available nutrients in the soil, nor in the efficiency of recovering available nutrients into the grain. Nevertheless, intercropped maize produced a higher grain yield per unit of absorbed nitrogen and potassium. This study showed that intercropping arable crops in walnut orchards could be a viable measure of intensifying agricultural production or a profitable way of transferring from crop to fruit production. However, the overall productivity and ecological and economic sustainability could greatly depend on the selection of species and the design of the system.

ŽIVOTOPIS

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CURRICULUM VITAE

Helena Žalac was born on September 1, 1994 in Đakovo, where she attended the A.G. Matoš secondary school. In 2013, she enrolled in the Undergraduate University Study in Horticulture at the Faculty of Agriculture in Osijek, J.J. Strossmayer University in Osijek, and in 2016 she obtained the academic title of Bachelor of Engineering Science in Agriculture (B.Eng.Sc. Agriculture). In the same year, she enrolled in a graduate course Plant production - Plant Nutrition and Soil Science, which she completed in 2018 with a defense of a thesis entitled Influence of the microbiological fertilizer application on the availability of organic phosphorus in the soil, thereby earning the academic title of Master of Engineering Science in Agriculture (M.Eng.Sc. Agriculture). Since March 2019, she has been employed on the project of the Croatian Science Foundation entitled Intercropping of wood species and agricultural crops as an innovative approach in agroecosystems (UIP-7103), under the leadership of Associate Professor Dr.Sc. Vladimir Ivezić. In the same year, he enrolled in the Postgraduate University Study of Agricultural Sciences, course of studies in Agrochemistry, at the Faculty of Agrobiotechnical Sciences Osijek. As an author or co-author, she published 5 scientific papers indexed in the Web of Science database and 8 papers represented in other bibliographic databases. She participated in several domestic and international scientific meetings, and attended three professional training courses as part of the Erasmus+ program (Wageningen University and Research - WUR, Netherlands; National Research Institute for Agriculture, Food and Environment - INRAE, France; The School of Agriculture - ISA, Portugal). As a collaborator, she also participated in the project Impact of the intercropping of short-rotation coppice and arable crops on soil fertility within the research team Diversification of Agriculture with Agroforestry Systems, led by Assoc. Ph.D. Vladimir Zebec. She is a member of the Croatian Soil Science Society (HTD) and the European Agroforestry Federation (EURAF)