UNIVERZA V LJUBLJANI

BIOTEHNIŠKA FAKULTETA

Peter ZADRAVEC

PRIRAST PLODOV KOT MODEL ZGODNJE NAPOVEDI PRIDELKA ŠTIRIH SORT ŽLAHTNE JABLANE (*Malus domestica* Borkh.)

DOKTORSKA DISERTACIJA

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FRUIT ENLARGEMENT AS A MODEL FOR EARLY YIELD PREDICTION OF FOUR APPLE CULTIVARS (*Malus domestica* Borkh.)

DOCTORAL DISSERTATION

Ljubljana, 2016

Na podlagi Statuta Univerze v Ljubljani ter po sklepu Senata Biotehniške fakultete in sklepa Komisije za doktorski študij Univerze v Ljubljani z dne 17. 2. 2015 je bilo potrjeno, da kandidat izpolnjuje pogoje za opravljanje doktorata znanosti na Interdisciplinarnem doktorskem študijskem programu Bioznanosti, znanstveno področje hortikultura.

Za mentorja je bil imenovan prof. dr. Franci Štampar.

Praktični del poskusov je bil izveden na Sadjarskem centru Maribor, KGZ Maribor.

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Datum zagovora:

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Peter ZADRAVEC

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OP IX, 50, [4] str., 8 pregl., 35 vir.

IJ sl

JI sl/en

AI Natančno napovedovanje pridelka jabolk je zaradi obilne svetovne pridelave (75.000.000 ton letno) in globalnega trženja plodov zelo pomembno. Z meritvami priraščanja plodov različnih sort ('Gala', 'Zlati delišes', 'Fuji' in 'Braeburn') smo želeli povečati natančnost napovedi ter ugotoviti povezanost priraščanja z notranjimi (genskimi) in zunanjimi (vpliv leta, vpliv položaja plodu, vpliv gostote oveska) dejavniki. V dveh večletnih poskusih na lokaciji N 46^{0}61', E 15^{0}69' smo s periodičnimi meritvami ekvatorialnega premera jabolk ugotovili, da krivulja priraščanja od T- stadija do tehnološke zrelosti kaže tipično negativno eksponentno obliko, ki pa je pri zgodaj zoreči sorti 'Gala' manj izrazita. Sorte 'Gala', 'Zlati delišes' in 'Fuji' imajo podobno priraščanje, medtem ko 'Braeburn' prirašča nekoliko počasneje. Končna dosežena velikost plodov ob tehnološki zrelosti je sortno pogojena in odvisna od leta. Natančnost napovedi končne velikosti plodov je večja pri kasneje zorečih sortah, pri njih tudi bolj zgodaj v rastni dobi natančno napovemo končno velikost (110 DAFB). Pri sorti 'Gala' niti različne gostote oveska (4 / 7/ 9 pl. na cm^2 preseka debla) in niti dolžina rastne dobe plodov (122–131 dni) nista imeli vpliva na končno velikost plodov. Na končno velikost plodov ima od zunanjih dejavnikov najbrž največji vpliv temperatura v času od 0 do 40 DAFB. Povprečni napovedovalni model po Welteju in Stanleyu je v dveh od treh let s 95% natančnostjo napovedal skupni pridelek. Za izboljšanje natančnosti bodo potrebne nadaljnje raziskave o povezanosti modelnih parametrov in zunanjih dejavnikov v začetku rastne dobe plodov.

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TI FRUIT ENLARGEMENT AS A MODEL FOR EARLY YIELD PREDICTION OF FOUR APPLE CULTIVARS (*Malus domestica* Borkh.).

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LA sl

AL sl/en

AB Because of the world production (75.000.000 tons per year) and global sales of fruit exact apple fruit forecast is necessary. By measuring the fruit growth rate of different apple cultivars ('Gala', 'Golden Delicious', 'Fuji' and 'Braeburn') we wanted to increase the accuracy of forecast and to discover the connection of fruit growth rate with inner (genetic) and external (influence of the season, position of the fruit, crop load density) factors. With two multiannual experiments located N $46^0$61', E $15^0$69' by periodical measurements of equatorial diameter of apples, we discovered that the curve of diameter increase from T-stadium to technological ripeness shows a typical negative exponential form which is less prominent with early ripening cultivar 'Gala'. Cultivars 'Gala', 'Golden Delicious' and 'Fuji' have similar stages of fruit growth rate while the fruit growth rate of 'Braeburn' is somewhat slower. The final size of fruits at their technological ripeness depends on the cultivar and the year. With later ripening cultivars the precision of the forecast of the final fruit size is more accurate, and it is easier to forecast the final fruit size (110 DAFB) early in their growing stage. With the cultivar 'Gala' neither the crop load density (4/7/9 fruits per cm^2 trunk cross-sectional area) neither the length of the growing period (122-131 days) did not influence the final fruit size. Probably the largest influence on the final fruit size, regarding the external factors, has the temperature during the growth period from 0 to 40 DAFB. The Welte and Stanley forecast model with included average parameters predicted the total crop with 95 % accuracy in two out of three years. To increase the accuracy, further research about the connection of model parameters with external factors, in the beginning of the growth period of fruit, will be necessary.

KAZALO VSEBINE

KAZALO ZNANSTVENIH DEL

Fruit growth patterns of four apple cultivars using nonlinear growth models. 2014. European Journal of Horticultural Science, 79, 2: 52-59

Fruit size prediction of four apple cultivars: accuracy and timing. 2013. Scientia Horticulturae, 160 : 177-181

Modeling of 'Gala' apple fruits diameter for improving the accuracy of early yield prediction. 2013. Scientia Horticulturae, 160: 306-312

KAZALO PREGLEDNIC

KAZALO PRILOG

KRATICE IN OKRAJŠAVE

DAFB	days after full bloom / dnevi po polnem cvetenju
FB	full bloom / polno cvetenje
HA	heat accumulation / vsota najvišje in najnižje dnevne temperature za določeno obdobje, izražena v ^{0}C
TCSA	trunk cross section area / površina preseka debla v cm^{2}
T – stadij	časovna točka, ko pecelj plodu in tangenta oboda plodu na tem mestu tvorita kot 90^{0}
SC Mb	Sadjarski center Maribor

1 UVOD

Jabolko je v svetovnem merilu eno od pomembnejših plodov (letna pridelava je ocenjena na približno 75.000.000 ton) in je takoj za banano (letna pridelava je ocenjena na 97.000.000 ton) na drugem mestu. V svetovni trgovini s sadjem predstavlja z 8.300.000 tonami pomemben izvozni artikel (World apple review, 2012). Je tudi eno od globalno trženih plodov in zaradi svojega pomena v svetovni trgovini s sadjem tudi eno redkih, ki mu je posvečena posebna pozornost z vsakoletno napovedjo pridelka.

Napoved pridelka se izvede v večini najpomembnejših držav pridelovalk na obeh hemisferah, doda se tudi ocena pridelka v državah, ki v ocenjevanju in napovedovanju sicer ne sodelujejo (Kitajska, Iran, Turčija, Indija), po pridelavi pa sodijo med deset največjih pridelovalk. Tako lahko zatrdimo, da obstaja za jabolka dokaj zanesljiva letna globalna napoved pridelka.

Slovenija v napovedi svetovnega pridelka jabolk in hrušk pod okriljem WAPA (World Apple and Pear Association) in Eurofel sodeluje že od leta 1992. V prvih dvanajstih letih je za Slovenijo izvedlo napoved GIZ Sadjarstvo Slovenije in pri tem uporabljalo t. i. Winterjevo metodo napovedi. Od leta 2004 pa so napoved pričeli izvajati na podlagi posodobljene metode z analizo slike (Stajnko in sod., 2011).

Znana in velikokrat potrjena je linearna zveza med številom plodov in maso pridelka na drevo (Elfing in sod., 1993). Najenostavnejše metode napovedovanja pridelka tako temeljijo na štetju plodov na vzorcu izbranih dreves ter izkustveno pričakovani masi povprečnega plodu. Iz teh podatkov dobimo po enostavnih izračunih približne ocene skupnega pridelka za posamezni nasad, nasade v regiji ali državi. Za potrebe prve skupne ocene pridelka jabolk v takratni EU so v poskusnem centru Bavendorf razvili t. i. Winterjevo ali Bavendorfsko metodo, ki temelji na oceni pridelovalne kapacitete sadovnjaka, meritvah gostote oveska plodov (število plodov v znano velikem vidnem polju dela krošnje) in ocenjeni povprečni masi plodu ob obiranju (Welte, 1994). V evropskem projektu »Prognosfruit« sodelujoče države ali regije na svojem ozemlju že več let napovedujejo svoj pridelek jabolk. Takšna napoved pogosto ni bila dovolj natančna, zabeležena so bila tudi odstopanja od –21,9 do + 14.1 % (Stajnko in sod., 2004) ali celo 15 do 40 % (Wulfson, 2012). Poleg tega je bil postopek meritev v nasadih zelo dolgotrajen in delovno intenziven. Za izboljšanje natančnosti meritev števila in velikosti plodov so razvili različne metode. V zadnjih letih se zaradi enostavnosti izvedbe najbolj uveljavlja metoda analize slike. Z njo je lahko dosežena tesna korelacija med ocenjenim in preštetim številom plodov r = 0,73 do 0,94 (Stajnko in sod., 2011). Na ta način je problem natančnosti in hitrosti ocene števila plodov na drevesih dobro rešen.

Za izboljšanje napovedovanja končne velikosti plodov je potrebno čim natančneje opisati priraščanje tržno najzanimivejših sort, izboljšati napovedovalni model končne velikosti plodov ter opredeliti njegovo zanesljivost in natančnost v posameznih razvojnih fazah.

Glede na pomembnost čim natančnejše napovedi pridelka je raziskav na tem področju pri novejših sortah relativno malo, to je bil dodaten motiv za našo raziskavo.

Pomemben dejavnik uspešnosti pridelave je velikost plodov jabolk v času tehnološke zrelosti. Vpliva na maso pridelanih plodov (zveza med premerom in maso plodov), opredeljuje njihovo tržno vrednost (razdelitev v kakovostne razrede), vpliva na učinkovitost obiranja plodov in s tem na organizacijo obiranja in skladiščenja, prav tako vpliva na skladiščno sposobnost plodov in na trženje plodov. Velikost plodov bi torej lahko opisali kot eno pomembnejših lastnosti jabolk.

S tehnološkega zornega kota nas zanimajo zakonitosti priraščanja plodov v odvisnosti od dejavnikov okolja in pridelovalnih tehnik. Z dobrim poznavanjem obojega bi lahko pravočasno reagirali na razmere v nasadu in z uporabo primernih ukrepov dosegli boljši pridelovalni uspeh.

Priraščanje plodov jabolk je med vsemi sadnimi vrstami najbolje raziskano. Raziskave v sedemdesetih letih prejšnjega stoletja so pokazale, da je končna velikost plodov v veliki meri odvisna od razmerja med listi in plodovi (gostota oveska plodov), da v hladni klimi plodovi za enako rast potrebujejo več listov, da je rast plodov v fazi od oplodnje do junijskega trebljenja odvisna predvsem od rezervnih snovi, in da ugodno razmerje med listi in plodovi vpliva na rast plodov šele po junijskem trebljenju (Silbereisen, 1966). Welte (1994) je v svoji raziskavi povzel, da številni poskusi napovedovanja končne velikosti plodov jablane, ki so za oceno upoštevali predvsem meteorološke dejavnike v rastni dobi (padavine, temperaturo, zračno vlago …), niso omogočili določitve zanesljivih rastnih krivulj. Zaradi številnih dejavnikov, ki na potek priraščanja vplivajo, jih je razdelil v skupino t. i. endogenih (fotosinteza, rast poganjkov, sorta, gostota oveska plodov, število celic, velikost celic, število semen, položaj plodov) in eksogenih vremenskih vplivov (svetloba in dolžina dneva, temperatura, padavine) ter eksogenih gojitvenih vplivov (gojitveni sistem in rez, varstvo rastlin in poškodbe od bolezni in škodljivcev, podlaga, rastišče in prehrana rastlin). Veliko število vplivov je raziskovalce vodilo k temeljitemu proučevanju njihove medsebojne odvisnosti. Danska raziskovalca (Kaack in Pedersen, 2010) sta proučevala vpliv klimatskih spremenljivk (vsota efektivnih temperatur, padavine, evaporacijski potencial, hitrost vetra, povprečna dnevna relativna vlažnost zraka, deficit parnega tlaka, globalna radiacija, temperatura tal, vlažnost listov) in njihovih interakcij na premer, maso in kakovost plodov sorte 'Elstar'. Statistično značilni vpliv na premer plodov ima vsota efektivnih temperatur in evaporacijski potencial.

Lakso in sod. (1995) so raziskovali vpliv zgodnjega redčenja plodičev na končno velikost plodov in obliko krivulje priraščanja plodov. Ugotovili so, da ekspolinearni model priraščanja po Goudriaanu in Monteithu dobro popiše realno priraščanje plodičev sort 'Empire' in 'Zlati delišes'. Zgodnje eksponentno priraščanje plodov pripisujejo eksponentnemu povečanju prestrežene svetlobe ob povečevanju listne površine. Kasnejše linearno povečevanje mase plodov pa povezujejo s konstantnim prestrezanjem svetlobe po dokončnem oblikovanju drevesne krošnje. Izmerjene razlike v končni velikosti plodov med močno in blago redčenimi drevesi pripisujejo predvsem medsebojni konkurenci plodičev za ogljikove hidrate v fazi celičnih delitev in posledično različnemu številu celic (Lakso, 1995).

Čeprav avtorji raziskav s tega področja poudarjajo veliko število različnih vplivov na potek priraščanja plodov je najpogosteje omenjeni dejavnik vendarle toplota. Še prav posebno velik vpliv ima toplota v prvi fazi razvoja plodičev – neposredno po oplodnji in po mnenju večine nekje do 40 dni po polnem cvetenju (40 DAFB). Tako so v poskusih v popolnoma nadzorovanem okolju rastnih komor na Novi Zelandiji (HFRI of New Zealand Ltd.) raziskali in pojasnili vpliv zgodnjih sezonskih temperatur na razvoj plodov pri jablani. Največje dnevno priraščanje plodičev v času med 10 DAFB in 40 DAFB pri srednji temperaturi 20 ^{0}C je bilo tudi do 10-krat večje kot pri temperaturi 6 ^{o}C (Warington in sod., 1999).

Vpliv gostote oveska plodov in termina izvedbe redčenja na potek priraščanja in končno velikost plodov pri sorti 'Empire' so proučevali na raziskovalnem centru Geneva, New York (Lakso in sod., 1995). Njihove ugotovitve kažejo, da imata tako ovesek kot tudi termin in intenzivnost redčenja učinek na končno velikost plodov. Poudariti je potrebno, da so primerjali zelo majhen ovesek (ocenjeni pridelek 15 t/ha) z dokaj visokim oveskom (ocenjeni pridelek 40–50 t/ha). Na univerzi Talca v Čilu (Yuri in sod., 2011) so proučevali vpliv gostote oveska plodov na rodni veji sorte 'Gala' na rast plodov, kakovost in vegetativno rast. V prvem letu so ob obremenitvah 5,3 / 6,7 / 8,0 pl./cm^2 TCSA dokazali statistično značilno razliko v doseženi masi plodov (179,1 a / 175,8 b / 170,2 b). V naslednjem letu ob obremenitvah 3,8 / 4,3 / 6,0 med obravnavanji ni bilo razlik. Še leto kasneje ob obremenitvah 4,4 / 5,2 / 6,4 pa sta bili enaki obravnavanji majhna in srednja obremenitev, masa plodov v najmanjši obremenitvi pa je bila statistično značilno večja od mase v največji obremenitvi (185,6 a / 179,6 ab / 171,0 b).

Za boljšo pojasnitev poteka priraščanja plodov in odvisnosti priraščanja od sorte ter gostote oveska plodov ter preverbe natančnosti in zanesljivosti enega od napovedovalnih modelov, smo postavili naslednje raziskovalne hipoteze:

- Dinamika priraščanja plodov je sortno (gensko) pogojena, zato okoljski dejavniki ne vplivajo bistveno na njen potek.
- Končno velikost plodov lahko z zadostno zanesljivostjo napovemo že 100 dni po polnem cvetenju.
- Ovesek plodov kot natančno opredeljeni tehnološki parameter odločilno vpliva na dinamiko priraščanja in končno velikost plodov.
- Napovedovalni model priraščanja lahko z zadovoljivo natančnostjo (95%) napove končno velikost plodov in s tem tudi skupno maso pridelka.

Da bi odgovorili na postavljene hipoteze, smo izvedli v poskusnih nasadih Sadjarskega centra Maribor, ki deluje v okviru Kmetijsko gozdarske zbornice Slovenije in Kmetijsko – gozdarskega zavoda Maribor, dva večletna poskusa. Poskusni nasad se nahaja na geografskih koordinatah 46,61 N; 15,69 E; na nadmorski višini 280 m. Drevesa so bila gojena v obliko ozkega vretena, nasad je bil pokrit s črno protitočno mrežo in namakan s kapljičnim namakalnim sistemom. Vsi gojitveni ukrepi so bili izvedeni v skladu z načeli integriranega pridelovanja. Vse sorte so bile cepljene na šibko rastočo vegetativno podlago M9.

PRVI POSKUS

Poskusni sadovnjak, v katerem smo izvedli prvi poskus, je bil posajen leta 2003 v enovrstnem sistemu sajenja, z razdaljo sajenja 3,0 m x 1,0 m, torej v gostoti 3.000 dreves/ha. S sortno prilagojenim kemičnim redčenjem in z naknadnim ročnim redčenjem pred doseženim T-stadijem smo drevesa, vključena v poskus, vsako leto obremenili s srednjo obremenitvijo (oveskom) plodov, izraženo v merilu 4–6 plodov na cm^2 preseka debla. V meritve priraščanja premera plodov smo vključili 4 tržno zanimive sorte jablan:

- Izbrane sorte spadajo med najbolj zastopane v sortimentu sodobnih nasadov jablan v Sloveniji (SURS, 2015), Evropi (Wapa, 2012) in tudi v svetu (WAReport, 2012).
- Sorte se po dozorevanju razvrščajo v tri skupine: 'Gala' (poznopoletna, zori v zadnji dekadi avgusta, 115 dni od cvetenja do zrelosti), 'Zlati delišes' (zgodnjejesenska, zori v prvi dekadi septembra, 140 dni od cvetenja do zrelosti), 'Fuji' (poznojesenska, zori v prvi dekadi oktobra, 178 dni od cvetenja do zrelosti), 'Braeburn' (poznojesenska, zori v prvi dekadi oktobra, 168 dni od cvetenja do zrelosti) (Wert, 2009:67).
- Sorte po pričakovani velikosti plodov sodijo v različne skupine:
  'Gala' Brookfield® (drobnoplodne do srednje debeli plodovi), 'Zlati delišes' Reinders® (debeloplodna), 'Fuji' Kiku® (debeloplodna), 'Braeburn' Hillwell® (srednje debeli do debeli plodovi) (Štampar in sod., 2005)

Izvedba meritev

Na naključno izbranih izenačenih drevesih (po 4 drevesa za vsako sorto) smo označili 10 plodov v treh različnih položajih: 3 plodovi – terminalni položaj na 30–40 cm dolgem poganjku; 4 plodovi – brstiči na dvoletnem lesu; 3 plodovi – brstike ali brstiči na triletnem lesu. Priraščanje plodov smo v rednih 5 do 7-dnevnih presledkih merili z digitalnim kljunastim merilom Prowin, HMTY0006 tako, da smo na vsakem plodu v območju največjega premera (ekvator plodu) izmerili premer dvakrat za 90^o zamaknjeno in zabeležili povprečni premer plodu. Prvo meritev smo izvedli ob ali takoj po T-stadiju in z meritvami nadaljevali do tehnološke zrelosti plodov. Plodove smo takrat obrali in posamično stehtali. Vse meritve smo izvedli v letih 2006, 2007 in 2008 na istih drevesih.

Analiza podatkov

Pred statističnim analiziranjem podatkov smo izločili vse meritve, ki zaradi predčasnega odpadanja plodičev niso bile popolne. 14,4 % podatkov je bilo izločenih iz nadaljnjih analiz. Premer plodov smo upoštevali kot odvisno spremenljivko, čas, ki smo ga normalizirali v obliko – število dni po polnem cvetenju (DAFB) – pa kot neodvisno spremenljivko.

Individualno priraščanje premera plodov smo opisali s pomočjo negativnega eksponentnega modela po von Bertalanffyju (1938), ki je teoretično ustrezna enačba za opisovanje izometrične rasti ob uporabi enodimenzionalnega parametra rasti, v našem primeru premera plodičev. Uporabljena je bila enačba:

$$D(t) = \varphi 1\left(1 - e^{\left(-e^{\varphi 2}(t-\varphi 3)\right)}\right) \qquad \dots (1)$$

$D_{(t)}$ – premer plodu ob terminu t (DAFB).

φ_1 – parameter asimptote krivulje (potencialna končna velikost plodu).

φ_2 – parameter naklona krivulje (odvisen od stopnje priraščanja).

φ_3 – parameter presečišča z osjo x.

Enačbo smo uporabili za vsak proučevani plod posebej (skupno 360 plodov, izločeni so bili plodovi, ki niso zrasli do konca), iz česar smo dobili omenjene parametre modela za vsak plod, za katerega so bili znani proučevani dejavniki (sorta, leto, položaj plodu). Da smo določili vpliv teh dejavnikov, smo posamezni parameter modela preizkusili s faktorsko analizo variance (Anova). Homogenost variance smo predhodno grafično testirali z uporabo okvirjev z ročaji in QQ grafov. Za določanje signifikantnosti razlik in interakcij smo uporabili Duncan *post-hoc* test. Vse analize smo opravili v R okolju, za izračun parametrov modela po plodovih smo uporabili razširitveni paket `nlme` (R Core Team, 2012).

Da bi bolje utemeljili razlike med zunanjimi vplivi v treh zaporednih letih opazovanj in njihov morebitni vpliv na potek priraščanja plodičev, smo natančno spremljali fenološki razvoj jablan (brstenje, polno cvetenje, T-stadij, datum obiranja) in meteorološke podatke za obdobje rastne dobe v vseh letih.

DRUGI POSKUS

Drugi poskus smo izvedli na sorti Gala Schniga®, cepljeni na podlago M9. Drevesa so bila posajena leta 2004 v enovrstnem sistemu, z razdaljo 3,2 m x 0,7 m. V zimi 2009 smo izbrali 12 izenačenih dreves z uniformno strukturo krošnje, s podobnim presekom debla (TCSA) in s podobnim volumnom krošnje. Drevesa smo po naključnem izboru razdelili v tri obravnavanja. Obravnavanje 1: nizka obremenitev – 4 plodovi/cm^2 TCSA; obravnavanje 2: srednja obremenitev – 7 plodov/cm^2 TCSA; obravnavanje 3: visoka obremenitev – 9 plodov/cm^2 TCSA. Vsako obravnavanje je zajemalo 4 drevesa, torej ponovitve. Za posamezno drevo smo izračunali število plodov, ki je ustrezalo željeni obremenitvi (izmerjen obseg debla 20 cm nad cepljenim mestom, določitev kvadrature preseka debla – TCSA in posledično število plodov na drevesu v skladu z obremenitvijo). Nato smo izvedli ročno redčenje in vzpostavili želeno obremenitev. Pred T-stadijem smo izbrali in označili 10 plodov v različnih položajih: 3 v terminalnem položaju na enoletnem dolgem poganjku; 4 na brstičih dvoletnih poganjkov in 3 na brstičih in brstikah triletnih poganjkov. Za izračun mase plodov smo izvedli meritve premera plodičev z enako tehniko kot v prvem poskusu. Presledki med meritvami so bili v tem poskusu 14-dnevni, s prvo meritvijo 40 dni po polnem cvetenju. Vse opisano smo v istem nasadu izvedli v vseh zaporednih letih izvajanja poskusa (2009, 2010, 2011).

Analiza podatkov:

Izvedli smo modeliranje mase plodov po funkciji, ki sta jo razvila Mitchell (1986) in Welte (1990):

$$W = A*d^B \qquad \dots (2)$$

W = masa v g; A = 0,4059; d = ekvatorialni premer plodu v cm; B = 2,9602

Za determiniranje krivulj priraščanja plodov smo uporabili modificirano Gompertzovo funkcijo po Welteju (1990) in Stanleyu in sod. (2000) v sledeči obliki:

$$D_{(t)} = 3{,}5 + \alpha*(1-e^{\beta t})^{\Upsilon} \qquad \dots (3)$$

Welte (1994) v svojem delu z naslovom 'Analiza in simulacija rasti jabolk' parametre modela opiše tako:

$D_{(t)}$ = premer plodu v mm; t = čas od polnega cvetenja do obiranja v dnevih.

α = rastni parameter, ki opiše največjo možno končno velikost plodu in predstavlja teoretično vrednost, saj zaradi tehnoloških potreb oberemo plodove preden je ta vrednost dosežena.

β = rastni parameter, ki določa, kako močno bo rast upadala, ko plod doseže največje povečanje svoje mase. Istočasno parameter vpliva na zamik časovne točke, ko je doseženo največje povečevanje mase plodu. Časovna točka največjega priraščanja premera plodu pri spremembi parametra β ostane skoraj na isti točki. Na učinek parametra β neposredno vpliva čas t (v dnevih od polnega cvetenja DAFB).

Υ = rastni parameter, ki predvsem določa zakasnitev rasti po cvetenju. Če je parameter velik, pomeni, da je prišlo do začetne upočasnitve rasti. V takšnem primeru je največje povečanje mase plodov doseženo kasneje.

Meteorološke podatke smo povzeli po meritvah agrometeorološke postaje na lokaciji Sadjarski center Maribor.

Statistično analizo podatkov – primerjavo po modelu ocenjenih vrednosti z izmerjenimi vrednostmi – smo primerjali po metodi parov (T-test, $p \leq 0,05$) s statističnim paketom IBM SPSS Statistics 21.0.

Z obdelavo in analizo zbranih podatkov bomo pomembno prispevali k boljšemu določanju krivulj priraščanja plodov še posebej zato, ker smo meritve izvedli na sortah, ki so pomembno zastopane v svetovnem sortimentu jabolk in so z izjemo sorte 'Zlati delišes' dokaj nove in raziskovalno manj obdelane, a za pridelovalce zelo zanimive. Z določanjem zanesljivosti napovedovanja končne velikosti plodov bomo pomembno vplivali na kakovost zgodnje ocene pridelka jabolk, ki je glede na pomen v svetovni trgovini s sadjem izjemno pomemben dejavnik za gospodarsko uspešnost pridelovanja in trženja. Z natančnim spremljanjem priraščanja plodov pri sorti 'Gala' Schniga® v odvisnosti od obremenitve dreves pa bomo z izboljšanim napovedovalnim modelom poskusili povečati natančnost napovedi.

Celotno opisano raziskovalno problematiko smo obravnavali v treh znanstvenih člankih, ki so predstavljeni v nadaljevanju.

2 ZNANSTVENI ČLANKI

2.1 PRIRAST PLODOV ŠTIRIH SORT ŽLAHTNE JABLANE Z UPORABO NELINERNIH MODELOV RASTI

Zadravec P., Veberič R., Štampar F., Schmitzer V., Eler K. 2014. Fruit growth patterns of four apple cultivars using nonlinear growth models. European Journal of Horticultural Science, 79, 2: 52-59

Poznavanje vzorca priraščanja plodov jabolk od zavezanja plodičev pa vse do zrelosti plodov je ključno za napoved končne velikosti in mase plodov. Razumevanje priraščanja je pomembno tudi za časovno in tehnološko pravilno izvedbo številnih gojitvenih ukrepov (redčenje plodov, varstvo rastlin, namakanje in obiranje). Pojasnjevanje poteka priraščanja lahko izboljša napoved končne velikosti plodov in s tem tudi zgodnje napovedi pridelka. Cilj naše raziskave je bil opisati priraščanje plodov štirih sort žlahtne jablane: zgodnjejesenske sorte 'Gala' Brookfield®, jesenske sorte 'Zlati delišes' Reinders® in poznojesenskih sort 'Fuji' Kiku® ter 'Braeburn' Hillwell® s primernim nelinearnim modelom in posebno pozornostjo na razlike in podobnosti med sortami in modelnimi parametri. Poskus smo izvedli na lokaciji Sadjarski center Maribor. Pri vsaki sorti smo odbrali 4 enako razvita in obložena drevesa ter na vsakem drevesu označili po 10 plodov na različnih pozicijah (3 terminalne na enoletnem poganjku 30–40 cm, 4 terminalne na brstikah dvoletnega poganjka in 3 terminalne na brstičih triletnega poganjka). V pet- do sedemdnevnih presledkih smo od T-stadija do zrelosti plodov s kljunastim merilom merili priraščanje ekvatorialnega premera plodov. Ugotovili smo, da pozicija plodu nima vpliva na vzorec priraščanja plodov. Krivulje priraščanja plodov pri vseh sortah in v vseh opazovanih letih kažejo tipično negativno eksponentno obliko in so med sortami in leti dokaj podobne. Sorte 'Gala', 'Zlati delišes' in 'Fuji' imajo podobno intenzivnost priraščanja (naklon krivulje), medtem ko sorta 'Braeburn' prirašča počasneje. Na podlagi naših meritev in analiz lahko zaključimo, da je negativno eksponentna oblika krivulje priraščanja tipična za vse opazovane sorte. Linearnemu povečevanju premera plodov v začetni fazi razvoja plodov sledi upočasnjeno priraščanje v zadnji fazi rasti. To upočasnjeno priraščanje pa je manj izrazito pri zgodaj zorečih sortah (v našem primeru 'Gala').

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Fruit Growth Patterns of Four Apple Cultivars Using Nonlinear Growth Models

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Summary

Fruit diameter increase was monitored in four apple cultivars during three consecutive years (2006–2008) from t-stage until harvest. Individual fruit diameter increase was described using a negative exponential equation. Fruit growth curves of early ('Gala Brookfield'), mid-season ('Golden Delicious Reinders') and late ripening apple cultivars ('Braeburn Hillwell', 'Fuji Kiku 8') were denoted with an appropriate nonlinear model and each model parameter was evaluated separately. Apple fruit analyzed in the present study exhibited a similar growth curve for all analyzed cultivars i.e. a linear increase in fruit diameter in the beginning of fruit growth, followed by a slow curvilinear enlargement towards the asymptote in the final stages of fruit growth a few weeks before technological maturity. Asymptote was significantly dependent on cultivar, exhibiting higher correlation between predicted final fruit diameter and measured fruit diameter at harvest for late ripening cultivars. Similar growth rates have been calculated for 'Gala Brookfield', 'Golden Delicious Reinders' and 'Fuji Kiku 8' and a slower growth rate was characteristic for 'Braeburn Hillwell' cultivar.

Key words. diameter increase – growth curves – *Malus domestica* – statistical model

Introduction

Advanced knowledge of apple fruit development from fruitlet to maturity is crucial for optimal prediction of year-to-year yields and fruit quality. Apple (*Malus domestica* Borkh.) fruit growth has been defined as sigmoidal increase in fruit diameter or fresh weight, although several authors describe it as curvilinear in the first stages of expansion followed by a steady linear increase (Lakso et al. 1995). This growth pattern closely resembles physiological development of apple fruit, which can be split into two distinct but interlocked processes; rapid cell division and a later, cell size increase (elongation and enlargement) (Austin et al. 1999). Authors report, that cell division in apple fruit ceases about 5 to 6 weeks after full bloom followed by cell expansion (Al-Hinai and Roper 2004).

Understanding general fruit growth pattern is important for timing of different technological processes in apple orchards. Fruit thinning, pest and disease control management, optimal irrigation and harvest, as well as other practices critically depend on the correct time of implementation (Westwood 2009; Kaack and Pedersen 2011). Moreover, elucidating apple growth curves can help set timestamps for potential fruit size prediction and, consequently yield forecast. The latter is needed for competitive advantages in fresh-market planning as a great yearly fluctuation is common in worldwide apple production (Wulfsohn et al. 2012). Yield forecasting with an input of field-survey or probability-based sampling data combine fruit counts and size measurements with pre-calculated growth curves and correlations between fruit diameter and mass (Wulfsohn et al. 2012; Zhou et al. 2012). The impact of several factors on apple growth curves has been monitored and determined. Among them temperature, long- or short-term water stress, and applied technological practices (thinning, hormone application) have been confirmed to influence apple development (Stern et al. 2003; Kaack and Pedersen 2010).

The competitiveness of apple fruit as a sink is related firstly, to the number of its cells and secondly, the physiological status (Lakso et al. 1995). These are determined not only by environmental factors or cultural practices but are also genetically predisposed. Cultivar, rootstock, plant age, biennial bearing, the position of the flower on spur potentially affect the final size of apple fruit (Lakso et al. 1995; Ferree et al. 2001; Atay et al. 2010). However, genetic determination of seasonal growth curves has rarely been studied although research focusing on rootstock-graft interactions and final apple size determination or quantification has been published (Al-Hinai and Roper 2004; Karlidag and Esitken 2012).

Growth has been described as an irreversible increase in weight and mass (Atay et al. 2010), and final apple size is pre-determined for specific apple cultivars. Although apple cultivars all bloom within a short but similar time period, mostly dependent on seasonal factors, apple growth and fruit maturation time varies substantially among cultivars. In temperate environments, early cultivars mature 70–90 days after full bloom (DAFB) and late cultivars 150–160 DAFB (Schechter et al. 1993). Differences in genetic and seasonal growth curves for early and late ripening apples have rarely been studied over a period of several years and mathematical models describing their specifics are still lacking.

The present study aims to describe apple fruit growth of early, mid-season and late ripening apple cultivars using an appropriate nonlinear model and draws attention to differences or similarities among cultivars in model parameters. The analysis and growth curve characterization expands through several consecutive years and includes data from the beginning of cell expansion stage onward elucidation the diameter increase of 4 apple cultivars until harvest at technological maturity. Model appropriateness is discussed. The study assesses eventual discrepancies between model-predicted final fruit size and real-time final fruit size of analyzed cultivars. The understanding of specific growth curves of widely planted apple cultivars can help fine tune pruning, fruit thinning, harvest, and the use of fertilizers, growth regulators or irrigation and evaluate yields in commercial orchards.

Materials and Methods

Location and plant material

Apple fruit growth was monitored in an orchard located at the Fruit Growing Center Gacnik near Maribor, NE Slovenia (latitude 46° 33' 17" N, longitude 15° 38' 48" E, altitude 280 m) over 3 consecutive years (2006, 2007, 2008). Climatic conditions were recorded on site during the analyzed years (Table 1). Four apple cultivars were included in the growth pattern study: early to mid-season ripening 'Gala Brookfield' and 'Golden Delicious Reinders', and late-ripening, 'Fuji Kiku 8' and 'Braeburn Hillwell' cultivars all grafted on M9 and trained to a slender spindle. The orchard was planted in 2003 at a density of approximately 3000 trees per hectare. The orchard was equipped with drip irrigation system, covered with black hail nets and managed according to integrated production measures. A crop density of 4–6 fruit per trunk cross-sectional area was ascertained by hand thinning prior to the first measurement at t-stage of fruit development. T-stage has been described as the phase when the underside of the fruit and stalk form the letter T (Blanke and Kunz 2009).

Sampling

Four trees per cultivar were randomly selected and the same trees were monitored each year to ensure equal measuring conditions. On each tree, 12 apples were individually labelled according to the characteristics of the fruiting wood: 1. Terminal bud on one-year-old wood (30–40 cm), 2. Terminal bud on two-year-old wood and, 3. Terminal bud on three-year-old wood. Per fruiting wood, 4 replicates were monitored for each tree at each sampling. Apple fruit growth (apple diameter, mm) was measured nondestructively at regular intervals (5–7 days) at the widest point of the fruit equatorial plane with a dig-

Table 1. Average monthly temperatures, temperature anomaly and total monthly precipitation and precipitation anomaly for collection site in years 2006, 2007 and 2008.

Measurements	Average monthly temperature (°C)			Temperature anomaly			Total monthly precipitation (mm)			Precipitation anomaly (%)		
Year	2006	2007	2008	2006	2007	2008	2006	2007	2008	2006	2007	2008
Apr	11.6	13.7	11.0	1.6	3.7	1.0	94	10	39	117	12	49
May	15.2	17.2	15.9	0.6	2.6	1.3	128	134	35	135	142	37
Jun	19.7	21.2	20.2	1.8	3.3	2.3	83	60	96	70	50	81
Jul	23.4	22.4	21.3	3.8	2.8	1.7	54	112	110	46	95	93
Aug	17.8	20.2	20.7	−0.9	1.5	2.0	137	129	134	106	100	105
Sep	17.4	13.9	14.9	2.2	−1.3	−0.3	73	173	61	74	175	62
Oct	12.9	9.5	11.6	2.8	−0.6	1.5	30	71	44	34	82	51

ital calliper. The first measurement was taken at t-stage of fruit development and the monitoring continued until fruit harvest at technological maturity (harvest maturity), when the mass of all sampled apples has also been recorded (Table 2).

Data analysis

Prior the further analysis data of all fruits which did not reach the technological maturity (fell off prematurely) were removed. 14.4 % of data was removed and data of 360 apple fruits was evaluated in forthcoming analyses. The diameter of apple fruits was regarded as a parameter of fruit growth and a response variable and time as independent variable. Time variable for all fruit growth data was normalized to days after full bloom (DAFB).

Individual fruit diameter growth patterns were described using negative exponential model. As show by von Bertalanffy (1938) this is theoretically the correct equation to describe isometric growth using one dimensional growth parameters such as fruit diameter. The following equation was used:

$$D(t) = \varphi_1\left(1 - e^{(-e^{\varphi 2}(t-\varphi_3))}\right) \qquad \text{[Eq. 1]}$$

D(t) fruit diameter at time t after full bloom
φ1 parameter, describing the asymptote of the curve (potential final fruit size)
φ2 parameter, determining the steepness of the curve (related to growth rate)
φ3 parameter, determining the intersection with the x-axis.

Next, each model parameter was individually compared between cultivars, years and fruiting wood using factorial ANOVA. Assumptions of ANOVA (homoscedasticity and normality) were tested graphically using boxplots and QQ-plots, rather than formally (Levene test, Sahiro-Wilk test) which almost always show significant deviations from normality and homoscedasticity for large sample sizes even when these deviations are trivial (Quinn and Keough 2002). Duncan post-hoc test was used to discriminate between significant factor effects and their interactions. All analyses were performed in R environment (R Core Team 2012). Nonlinear models were fitted using the library nlme.

Results and Discussion

Fruit diameter data collected at defined intervals from t-stage until fruit harvest were combined into a unified model illustrating growth curves for all analyzed cultivars. Of the factors being evaluated fruiting wood had no effect on growth curve parameters so it was excluded from the forthcoming analyses. Growth patterns seem fairly similar among cultivars and years (Fig. 1) and show a negative exponential shape. The parameters of the average model according to the equation 1 across all cultivars, fruiting woods and years are the following (mean estimate and 95 % confidence interval): φ1: 93.5 (92.2 – 94.8), φ2: –4.43 (–4.46 – –4.41) and φ3: 9.2 (8.75 – 9.65). Coefficient of determination (R2) of the average model is 91.3 % and means squared error is 0.997. The pairwise correlations between parameters were lower than 0.65 so we did not regard the model being overparameterized. As checked graphically (not shown here), deviations from normality and homoscedasticity assumptions were minor or lacking which justifies the use of ANOVA. ANOVA was calculated for each parameter separately to evaluate the impact of analyzed factors on general apple growth curve (Table 3). Of three parameters evaluated only parameters φ1 and φ2 are discussed for their biological significance. Parameter φ3 shifts the curve in × direction and is not regarded biologically explainable (otherwise it is related to initial fruit diameter). Predicted final fruit dia-

Table 2. Onset of full bloom, T-stage and harvest maturity, and the number of measurements taken each year for individual apple cultivar.

Cultivar/ Measurements	'Braeburn Hillwell'			'Fuji Kiku 8'			'Gala Brookfield'			'Golden Delicious Reinders'		
Year	2006	2007	2008	2006	2007	2008	2006	2007	2008	2006	2007	2008
Full bloom	Apr 26th	Apr 17th	Apr 18th	Apr 28th	Apr 17th	Apr 21st	Apr 27th	Apr 16th	Apr 21st	Apr 30th	Apr 17th	Apr 22nd
T-stage	May 21st	May 7th	May 12th	May 24th	May 10th	May 15th	May 21st	May 7th	May 13th	May 16th	May 11th	May 16th
Harvest maturity	Oct 10th	Sep 26th	Sep 24th	Oct 10th	Sep 26th	Sep 24th	Sep 5th	Aug 16th	Aug 28th	Sep 26th	Sep 12th	Sep 17th
No of sampling dates	21	21	18	21	21	18	16	15	14	19	19	17

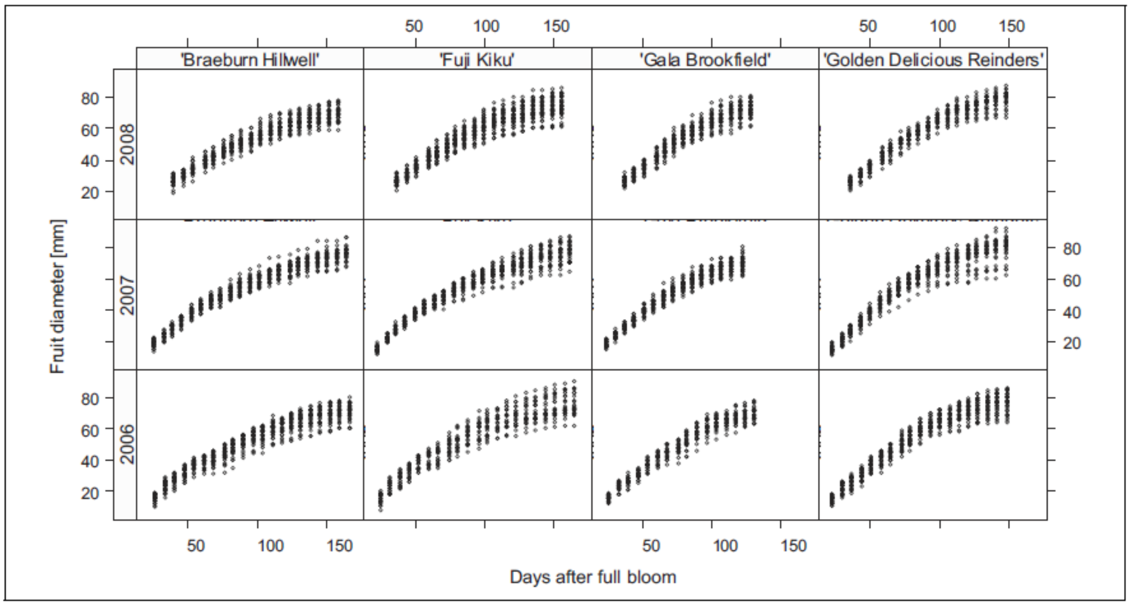

Fig. 1. Growth patterns of 360 investigated apple fruits of four cultivars in three consecutive years.

Table 3. ANOVA table calculated for each parameter and their interactions to predict the impact of analyzed factors on general apple growth curves.

ANOVA	φ1			φ2			φ3		
	df	F value	P-value	df	F value	P-value	df	F value	P-value
Cultivar	3	9.428	0.000	3	9.969	0.000	3	44.631	0.000
Year	2	1.422	0.243	2	8.689	0.000	2	35.65	0.000
Position	2	0.155	0.856	2	0.362	0.697	2	7.548	0.063
Cultivar:year	6	2.338	0.032	6	1.74	0.111	6	2.698	0.014
Cultivar:position	6	1.085	0.371	6	0.809	0.563	6	0.317	0.928
Year:position	4	0.307	0.873	4	0.901	0.464	4	1.732	0.143
Cultivar:year:position	12	1.284	0.226	12	2.054	0.020	12	1.148	0.320

meter (parameter φ1) was significantly dependent on cultivar and a weak cultivar:year interaction has also been confirmed (Fig. 2). This suggests that the final model-predicted fruit diameter (described by the asymptote of the curve) is genetically controlled and is affected to a moderate extent by other internal and external analyzed factors. Interestingly, the asymptote for early-ripening cultivar 'Gala Brookfield' and mid-season ripening 'Golden Delicious Reinders' was determined significantly higher compared to late-ripening 'Fuji Kiku 8' and 'Braeburn Hillwell'. The theoretical model-predicted final fruit diameter for early ripening cultivars differs greatly from fruit diameter at technological maturity reported by different authors (Atay et al. 2010; Ozkan et al. 2012). It can be speculated that early-ripening cultivars reach technological maturity relatively early in their development and their growth would continue beyond the technological maturity. It is generally known that 'Gala' strains in particular vary significantly in final fruit diameter over years being greatly dependent on temperatures, location and other environmental factors (Warrington et al. 1999). Additionally, it is computationally difficult to estimate the asymptote of fruit growth where the growth stops by early technological maturity; in some years (e.g. 2006 for 'Gala Brookfield') the growth seems almost linear (Fig. 1). On the other hand, the model-predicted asymptote (parameter φ1) for late-ripening 'Fuji Kiku 8' and 'Braeburn Hillwell' better fits the diameter at harvest reported by Talaie et al. (2011). Also, R2 for 'Fuji Kiku 8' apples describing the correlation between predicted

	φ1			φ2			φ3		
ANOVA	df	F value	P-value	df	F value	P-value	df	F value	P-value
Cultivar	3	9.503	0.000	3	9.434	0.000	3	43.909	0.000
Year	2	1.333	0.265	2	8.839	0.000	2	32.969	0.000
Cultivar:year	6	2.336	0.032	6	1.684	0.124	6	2.671	0.015

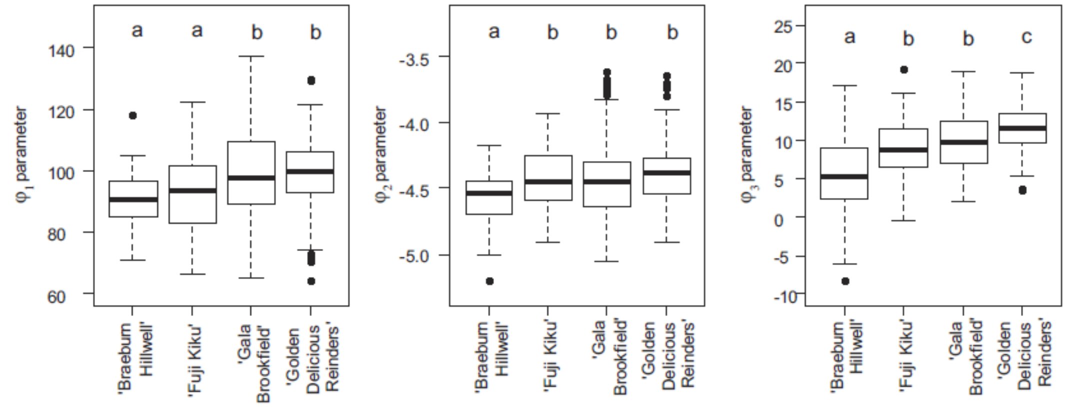

Fig. 2. ANOVA results and homogeneous groups for cultivar factor of individual model parameter describing apple fruit growth.

upper asymptote and observed (measured) fruit diameter was significantly higher compared to other cultivars (Fig. 3).

However, the inherent growth potential, or specifically the prospective final fruit diameter of selected cultivars described by the growth asymptote (parameter φ1) has to be distinguished from actual final growth. Namely, model predictions always describe growth under optimal conditions but in reality limited resources and competition from other sinks determine final apple fruit diameter (Lakso et al. 1995). Modeling approaches, elucidating apple fruit growth, thus report complex connections among external factors influencing final harvest size (Welte 1990; Lakso et al. 1995) but all agree on the major importance of internal i.e. genetic limitations to diameter increase similarly to the present model. The difference between asymptote and actual final diameter is larger for early ripening cultivars.

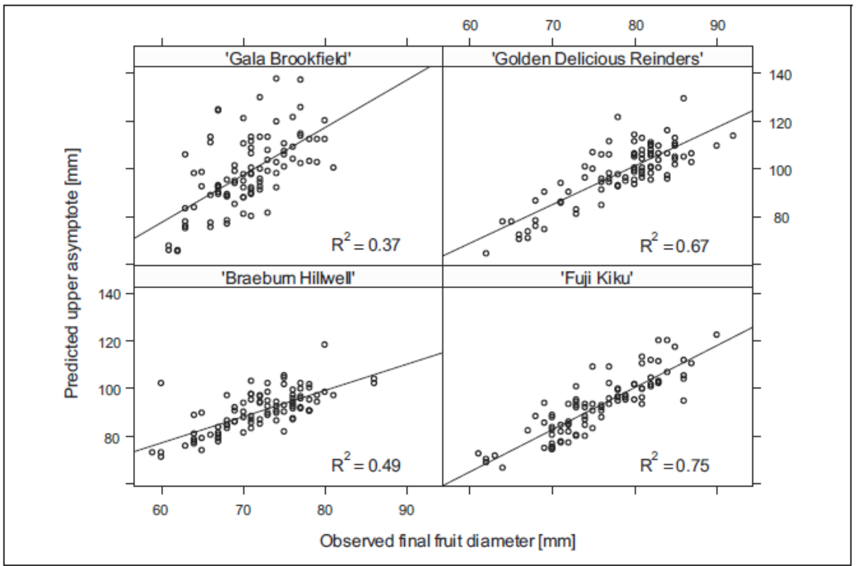

Fig. 3. Relationship between observed final apple fruit diameter and upper asymptote predicted on the basis of diameter growth data of individual apple fruits of four investigated cultivars.

Parameter φ2, determining the slope of the curve, shows the growth rate of the analyzed cultivars (Fig. 2). Again, the differences have been confirmed for cultivar and year, but no interaction has been determined. Similar growth rates have been calculated for 'Gala Brookfield', 'Golden Delicious Reinders' and 'Fuji Kiku 8'. A slower growth rate was characteristic for late-ripening 'Braeburn Hillwell' cultivar. A similar time-dependent diameter change (growth rate) has been demonstrated in a study of Atay et al. (2010) who compared 'Galaxy Gala' and 'Braeburn' cultivar. The latter demonstrated a different growth dynamics to that of early-ripening cultivars.

The modeled growth pattern describes the diameter increase of analyzed cultivars following the exponential cell division phase, which is reportedly curvilinear (Lakso et al. 1995). Namely, during the first 3–6 weeks apple size increase is largely a result of cell number multiplication and the fruit growth is slow (Lakso et al. 1995; Al-Hinai and Roper 2004). After t-stage (physiologically and practically dividing the two distinct growth phases) the increase in apple fruit diameter can predominately be ascribed to vacuolization of cells, individual cell size increase and rapid development of intercellular spaces (Warrington et al. 1999) and approximately linear growth pattern has been reported (Atay et al. 2010). This has also been confirmed by Goudriaan and Monteith (1990) who linked the linear increase with constant light interception after tree canopy closure. Apple development in the second (cell expansion) phase is thus primarily uniform but a late-season decline in fruit diameter increase has also been detected (Lakso et al. 1995). Apple fruit analyzed in the present study exhibited a similar growth curve (diameter increase) for all evaluated cultivars (Fig. 1). Firstly, it demonstrated a linear increase in fruit diameter followed by a slow curvilinear enlargement towards the asymptote. All cultivars are thus characterized by a slow growth rate in the final stages of fruit growth a few weeks before technological maturity. However, in 'Gala Brookfield' the linear diameter increase was extended until only several days prior to harvest.

Growth curve shape of biological data strongly depends on growth measure being evaluated. As shown by von Bertalanffy (1938) organism length follows negative exponential curve which has its mechanistic background. Fruit diameter is, similarly as an organism length, 1-dimensional measure of size so von Bertalanffy's model can be applicable also to fruit diameter growth data. This model describes the growth well when growth is isomorphic (no temporal change of shape) which holds for the apple fruit quite well too. In some papers such negative exponential curve shapes of fruit diameter growth were used (Warrington et al. 1999; Austin et al. 1999) although sometimes different (inappropriate) equations were also used to describe this measure of growth (Garriz et al. 1999).

As discussed previously, growth is a three-dimensional increase of an object so when studying growth of apple fruits the volume or fresh weight are often measured (Schechter et al. 1993; Lakso et al. 1995; Chakespari et al. 2010). The problem of this approach, however, is the destructiveness of the measurements which precludes the monitoring of the same fruits through time. To overcome this problem the diameter or weight might be estimated using known diameter-volume or diameter-weight relationships (De Silva et al. 1997; Warrington et al. 1999). By definition, the relationship between apple fruit diameter and volume/weight is third-order polynomial. Because the most appropriate growth model should follow mechanistic rules, for volumetric growth such a model can be obtained by combining equation 1 with the equation of the sphere:

$$V(t) = \frac{\pi}{6}\varphi_1^{\,3}\left(1 - e^{(-e^{\varphi 2}(t-\varphi_3))}\right)^3 \qquad \text{[Eq. 2]}$$

and for weight growth simply multiplying the equation 2 with apple fruit density ($\rho \approx 0.75–0.85$ g cm^{-3}):

$$W(t) = \rho\frac{\pi}{6}\varphi_1^{\,3}\left(1 - e^{(-e^{\varphi 2}(t-\varphi_3))}\right)^3 \qquad \text{[Eq. 3]}$$

Additionally, a correction factor can be added for asphericity of the apple fruit and for density changes during fruit growth. This, however, does not change the general curve shape of all analyzed cultivars which is asymmetric sigmoidal (Fig. 4). This specific model type has rarely been applied to apple fruit growth so far. Purely empirical expolinear (Lakso et al. 1995) or even (segmented) linear (Schechter et al. 1993) models were rather used. These predict constant fruit growth till maturity and no decrease in growth rate (upper asymptote) and describe fruit growth well for a given narrower period of growth. Upper asymptote of weight or volume is rarely traceable since fruits reach their maturity beforehand especially early ripening apple varieties, such as 'Gala Brookfield', in our case.

Divergence of real data from predicted values of models after equations 1, 2 and 3 is possible also due to suboptimal environmental conditions. Presence of drought, heat, pests, nutrient limitation, suboptimal light conditions, excessive fruit load can strongly affect fruit growth resulting in unusual growth curves (e.g. double sigmoidal).

It can, however, be concluded that a negative exponential growth pattern is universal for apple cultivars growing in typical circumstances. A linear increase in fruit diameter in the beginning of fruit growth is followed by a somewhat slower enlargement in the final stages of fruit growth. Interestingly, early ripening cultivars, such as 'Gala Brookfield' analyzed in the study, are characterized by a relatively linear increase of fruit diameter up until harvest. Theoretically, early-ripening cultivars reach technological maturity relatively quickly and their growth could continue beyond that set time-stamp. Slight differences in growth patterns of early- and late-ripening cultivars during fruit development should be considered for optimal apple orchard management.

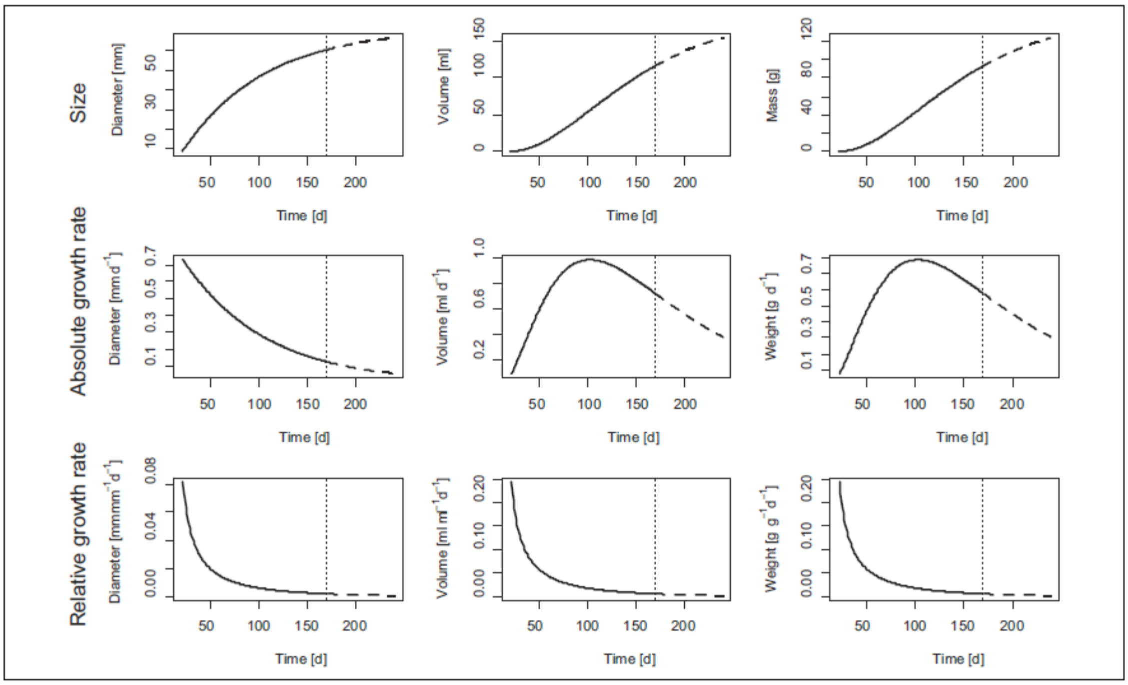

Fig. 4. Curves describing the growth of an average 'Fuji Kiku' apple fruit. Temporal changes of size, absolute and relative growth rate are showed for three measures of growth: diameter, volume and mass. For diameter growth a negative exponential model proposed by von Bertalanffy (1938) is used (Equation 1). All other curves result from this curve on the basis of mathematical and physical diameter-volume-mass relationships.

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2.2 NAPOVEDOVANJE VELIKOSTI PLODOV ŠTIRIH SORT ŽLAHTNE JABLANE: TOČNOST IN PRAVOČASNOST

Zadravec P., Veberič R., Štampar F., Eler K., Schmitzer V. 2013. Fruit size prediction of four apple cultivars: accuracy and timing. Scientia Horticulturae, 160: 177-181

Zgodnja napoved pridelka jabolk je pomembna za organizacijo dela ob obiranju, za skladiščenje in za načrtovanje trženja. Najpogosteje je napoved pridelka izvedena s štetjem plodov na izbranem vzorcu dreves in subjektivno izkustveno oceno pričakovane velikosti in mase plodov ob obiranju. Takšno ocenjevanje je dokaj nenatančno, zabeležena so odstopanja od 15 do 40 %. Cilj naše raziskave je bil, s pomočjo korelacijske in regresijske analize, določiti odnos med izmerjenim in napovedanim premerom in maso plodov ter oceno najzgodnejše primerno natančne napovedi končne velikosti in mase plodov. Da bi upoštevali morebitne razlike med sortami, smo v raziskavo vključili štiri različne sorte žlahtne jablane: zgodnjejesenske sorte 'Gala' Brookfield®, jesenske sorte 'Zlati delišes' Reinders® in poznojesenski sorti 'Fuji' Kiku® in 'Braeburn' Hillwell®. Poskus smo izvedli na lokaciji Sadjarski center Maribor. Pri vsaki sorti smo odbrali 4 enako razvita in obložena drevesa ter na vsakem drevesu označili po 10 plodov na različnih pozicijah (3 terminalne na enoletnem poganjku 30–40 cm, 4 terminalne na brstikah dvoletnega poganjka in 3 terminalne na brstičih triletnega poganjka). V pet- do sedemdnevnih presledkih smo od T-stadija do zrelosti plodov s kljunastim merilom merili priraščanje ekvatorialnega premera plodov. Ugotovili smo, da je v povprečju vseh opazovanih let 'Zlati delišes' dosegel največjo velikost in maso plodov, sledi mu 'Fuji', na tretjem mestu sta enako velika in težka 'Gala' in 'Braeburn'. Zabeležili smo tudi vpliv interakcije leto–sorta in sklepamo, da se sorte specifično odzovejo na meteorološke razmere leta. Za vse sorte, z izjemo Gale, je leto 2007, ki je bilo v obdobju od aprila do junija občutno toplejše od ostalih dveh let, dalo najdebelejše plodove. Ugotovili smo tudi, da za pozno zorečo sorto 'Braeburn' lahko bolj zgodaj v rastni dobi (91–98 DAFB) natančno (r^2 = 0,85) napovemo končno velikost plodov. Za ostale tri sorte to natančnost dosežemo šele od 112 do 126 DAFB. Kaže, da je zanesljivost napovedi končne velikosti plodov, ki sloni le na meritvah priraščanja plodov, zadovoljivo natančna v relativno pozni fazi razvoja plodov.

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Fruit size prediction of four apple cultivars: Accuracy and timing

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ABSTRACT

Apple fruit diameter and final fruit mass were monitored from T-stage until harvest over three consecutive years to assess the accuracy of fruit diameter prediction at several timestamps during apple fruit development. Four apple cultivars were selected for the study: 'Golden Delicious Reinders', 'Gala Brookfield', 'Fuji Kiku 8' and 'Braeburn Hillwell'. Moreover, fruits were selected according to the characteristics of the fruiting wood: (1) terminal bud on one-year-old wood (30–40 cm), (2) terminal bud on two-year-old wood, and (3) terminal bud on three-year-old wood. The prime influence on the final fruit size has been determined for cultivar, with great differences also detected among the analyzed years. Final fruit diameter and fruit mass were positively correlated in all analyzed cultivars. Position of the fruiting wood had a minor impact on final apple fruit size and the growth analysis of apple fruit revealed a uniform growth rate regardless of the position. Important cultivar-specific accuracy of yield prediction has been established with statistically significant correlations at an early stage of apple fruit growth but variable accuracy between early- and late-ripening cultivars.

1. Introduction

Fruit growth monitoring and apple (*Malus domestica* Borkh.) size quantification is important for several purposes such as prediction of potential fruit size and, consequently yield as well as for the use in crop simulation models. Early production forecasting in apple fruit orchards is essential for labor and market planning as a great yearly fluctuation is common in worldwide apple production (Wulfsohn et al., 2012). In Europe, about 10 million t of apple are harvested every year (Stajnko et al., 2009) and advance knowledge on fruit yield early in the season sets important parameters such as price, distribution, availability and other specifics (cultivars, sales-planning, storage potential) of apple production.

Typically, yield estimation is performed manually on selected trees and is also linked to previous observations and weather conditions. In practice, most individual growers predict the prospective apple yield based on visual and quite subjective observations of several trees and uncertainties of 15–40% are quite common (Wulfsohn et al., 2012). However, major fruit producing countries utilize yield forecasting with an input of field-survey or probability-based sampling data. Early prediction models combine fruit counts and size measurements with pre-calculated growth curves and correlations between fruit diameter and mass (Wulfsohn et al., 2012). Several apple yield prediction models have been developed comparing real-time fruit size with reference data at equivalent periods in previous years forecasting fruit size and mass by simple linear or complex curvilinear projections (Austin et al., 1999; Chakespari et al., 2010). Generally, seasonal estimates of apple yield are done in the beginning of July but producers and marketers strive to shift the prediction to earlier stages. However, apple fruit development consists of two distinct but interlocked processes; cell division and cell size increase (elongation and enlargement) (Austin et al., 1999) and physiologically, the rate of cell division later determines final fruit size (Goffinet et al., 1995). Thus, early-season conditions strongly influence the potential size of apples at harvest (Austin et al., 1999) and accurate forecasts can only be achieved far along in apple development frequently. So how late is still adequate and how early sufficiently accurate?

In the present paper a correlation/regression analysis determining the relationship between real-time apple diameter and final fruit size (and mass) has been evaluated in order to estimate the earliest prediction time and/or its uncertainty. To consider unique cultivar characteristics which determine the quality of forecast models (Atay et al., 2010), four different apple cultivars were investigated. Apple growth rate, maturation time, potential fruit size and prospective yield are genetically controlled factors which can be altered by cultivation practices and environmental conditions

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only to some extent. The aim was thus to elucidate the differences in early-estimation accuracy for 'Golden Delicious Reinders', 'Gala Brookfield', 'Fuji Kiku 8' and 'Braeburn Hillwell' and evaluate the prediction accuracy at several timestamps of apple fruit development.

2. Materials and methods

2.1. Location and plant material

The study was carried out over three consecutive years (2006–2008) in an apple orchard located at the Fruit Growing Center Gacnik near Maribor, NE Slovenia (latitude 46.61 N, longitude 15.69 E, altitude 280 m). Climatic conditions were recorded on site during the analyzed years (Table 1). Four apple cultivars were selected for the study: 'Golden Delicious Reinders', 'Gala Brookfield', 'Fuji Kiku 8' and 'Breaburn Hillwell'. 'Golden Delicious' cultivar is one of the most frequently planted apple cultivar in Europe and is relatively early, preceded only by 'Gala' strains, which are also rising in importance. Braeburn and Fuji strains have been selected for the analysis due to their late-ripening and favorable planting trends in Europe. The orchard was planted in 2003 at a density of approximately 3000 trees per hectare. Trees were grafted on M9 and trained to a slender spindle. The orchard was equipped with drip irrigation system, covered with black hail nets and managed according to integrated production measures. A crop density of 4–6 fruit per trunk cross-sectional area was ascertained by hand thinning prior to the first measurement at T-stage of fruit development. T-stage has been described as the phase when the underside of the fruit and stalk form the letter T (Blanke and Kunz, 2009).

2.2. Sampling

Four trees per cultivar were randomly selected and the same trees were monitored each year to ensure equal measuring conditions. On each tree, 12 apples were individually labeled according to the characteristics of the fruiting wood: (1) terminal bud on one-year-old wood (30–40 cm), (2) terminal bud on two-year-old wood, and (3) terminal bud on three-year-old wood. Per fruiting wood, four replicates were monitored for each tree at each sampling. Apple fruit growth (apple diameter, mm) was measured nondestructively at regular intervals (5–7 days) at the widest point of the fruit equatorial plane with a digital caliper. The first measurement was taken at T-stage of fruit development and the monitoring continued until fruit harvest at technological maturity, when the mass of the apples has also been recorded (Table 2).

2.3. Data analysis

Factorial ANOVA was used to investigate the effects of apple cultivar, year and bud/fruit position and their interactions. Duncan post hoc test at $\alpha = 0.05$ was used to derive homogeneous groups of significant factor and interaction levels. Before the ANOVA, the homoscedasticity was tested using Levene test at $\alpha = 0.05$.

To determine the possibilities of early-yield prediction, regression analysis was performed where final fruit diameter (D_f) was regressed against the fruit diameter at certain time after full bloom (D_t). No effect of bud position and sampling year on correlations between D_f and D_t was ascertained so fruits of all bud positions and all years of each cultivar were taken into account to derive the linear models. Weekly time step was used for calculations starting with day 21 after full bloom (dafb). Coefficient of determination (R^2) was calculated as the measure of goodness of model fit and accuracy of size prediction. Additionally, significance of correlation was calculated using the correlation test.

Final mass (M_f) prediction was performed similarly as final diameter; model fits were again evaluated using R^2.

Data were analyzed in R environment (R Core Team, 2012).

3. Results and discussion

3.1. The analysis of final fruit size

The fruits were harvested at technological maturity from mid-August to mid-October, depending on year and cultivar (Table 2) and diameter and mass of individual fruit were recorded. The final fruit diameter varied significantly among cultivars, years and positions (Table 3). Additionally, a year–cultivar interaction has been recorded suggesting that cultivars react specifically to meteorological conditions of a particular year – a general and expected behavior of genetically distinct material previously reported for various plants (Manakasem and Goodwin, 2001; Hampson et al., 2009; Farnham and Bjorkman, 2011). The prime influence on the final fruit size (diameter and mass) has been determined for cultivar, with great differences among the analyzed apple cultivars (Tables 3 and 5). 'Golden Delicious Reinders' cultivar was characterized by the largest fruit diameter and mass at technological maturity, followed by 'Fuji Kiku 8', 'Braeburn Hillwell' and 'Gala Brookfield' cultivar. This sizing order is in accordance with the reports of several authors monitoring fruit size of selected apple cultivars (Altuntas et al., 2012; Ozkan et al., 2012; Schupp et al., 2012) although certain authors report somewhat smaller fruit diameter for different 'Fuji' strains (Talaie et al., 2011). These discrepancies in fruit diameter and mass could be explained by major dependence on environmental conditions, location and also genetic factors (cultivars, strains) which differed among the research reports.

Similarly, in our study significant differences in final fruit diameter and mass at harvest have been determined among the analyzed years and cultivars (Fig. 1). The late ripening 'Braeburn Hillwell' and 'Fuji Kiku 8' cultivars were considerably affected by the yearly conditions: the highest final fruit size of both cultivars was measured in 2007. Equally, the largest fruit diameter and mass of 'Golden Delicious Reinders' were monitored in 2007. However, early ripening

Table 1
Average monthly temperatures, temperature anomaly and average monthly precipitation and precipitation anomaly for collection site in years 2006, 2007 and 2008.

Measurements	Average monthly temperature (°C)			Temperature anomaly			Average monthly precipitation (mm)			Precipitation anomaly (%)		
Year	2006	2007	2008	2006	2007	2008	2006	2007	2008	2006	2007	2008
April	11.6	13.7	11.0	1.6	3.7	1.0	94	10	39	117	12	49
May	15.2	17.2	15.9	0.6	2.6	1.3	128	134	35	135	142	37
June	19.7	21.2	20.2	1.8	3.3	2.3	83	60	96	70	50	81
July	23.4	22.4	21.3	3.8	2.8	1.7	54	112	110	46	95	93
August	17.8	20.2	20.7	–0.9	1.5	2.0	137	129	134	106	100	105
September	17.4	13.9	14.9	2.2	–1.3	–0.3	73	173	61	74	175	62
October	12.9	9.5	11.6	2.8	–0.6	1.5	30	71	44	34	82	51

Table 2
Onset of full bloom, T-stage and harvest time, and the number of measurements taken each year for individual apple cultivar.

Cultivar/measurements	'Braeburn Hillwell'			'Fuji Kiku 8'			'Gala Brookfield'			'Golden Delicious Reinders'		
Year	2006	2007	2008	2006	2007	2008	2006	2007	2008	2006	2007	2008
Full bloom	April 26th	April 17th	April 18th	April 28th	April 17th	April 21th	April 27th	April 16th	April 21th	April 30th	April 17th	April 22th
T-stage	May 21st	May 7th	May 12th	May 24th	May 10th	May 15th	May 21st	May 7th	May 13th	May 16th	May 11th	May 16th
Harvest time	October 10th	September 26th	September 24th	October 10th	September 26th	September 24th	September 5th	August 16th	August 28th	September 26th	September 12th	September 17th
No. of sampling dates	21	21	18	21	21	18	16	15	14	19	19	17

Table 3
Homogeneous groups for final fruit diameter of main effects and significant interactions derived using Duncan post hoc test at $\alpha = 0.05$ after factorial ANOVA.

Average diameter ± standard error and homogeneous groups			
Position ($p = 0.022$)			
1	72.9 ± 0.6 b		
2	74.2 ± 0.5 ab		
3	75.0 ± 0.6 a		
Cultivar ($p = 0.000$)			
'Golden Delicious Reinders'	78.3 ± 0.7 a		
'Fuji Kiku 8'	75.7 ± 0.7 b		
'Braeburn Hillwell'	72.0 ± 0.6 c		
'Gala Brookfield'	70.6 ± 0.5 c		
Year ($p = 0.003$)			
2007	75.4 ± 0.6 a		
2006	73.3 ± 0.6 b		
2008	73.5 ± 0.5 b		
Cultivar:year interaction ($p = 0.000$)			
	2006	2007	2008
'Braeburn Hillwell'	70.9 ± 0.9 e	76.2 ± 0.8 bc	69.2 ± 0.8 e
'Fuji Kiku 8'	76.2 ± 1.5 bc	77.1 ± 1.1 abc	74.4 ± 1.0 cd
'Gala Brookfield'	69.7 ± 0.9 e	69.8 ± 0.8 e	72.2 ± 0.8 de
'Golden Delicious Reinders'	76.6 ± 1.1 bc	79.8 ± 1.4 a	78.9 ± 0.9 ab

'Gala Brookfield' cultivar did not exhibit a similar trend and the largest fruit of this cultivar were measured in 2008. It seems that early-season conditions have a strong influence particularly on the final fruit diameter and mass of early-ripening cultivars and affect late ripening apple cultivars to a lesser extent (Austin et al., 1999). The final fruit size of 'Braeburn Hillwell', 'Fuji Kiku 8' and 'Golden Delicious Reinders' could be ascribed to increased photosynthesis and efficient resource allocation in the last phases of apple fruit growth (Austin et al., 1999). Similarly, in a study of Ferree et al. (2001) and Fallahi et al. (2011) the final fruit size of different late-ripening apple cultivars was greatly affected by diverse site conditions.

A moderate effect on final fruit diameter (but not on final fruit mass) has also been detected for bud/apple position on the tree but no position:cultivar interaction has been determined suggesting a similar behavior of all analyzed apple cultivars (Table 3). Terminal bud on one-year-old wood (30–40 cm) yielded fruit with smallest diameter at harvest but no differences between short fruiting wood on two-year-old or three-year-old shoots were detected. This positional influence can be effectively utilized in apple pruning as several authors report that an increased percentage of short fruiting wood in 'Fuji' apple also leads to better control of vegetative and reproductive growth and larger fruit (Asada, 1999, 2004).

3.2. *Fruit size prediction and correlations*

Fruit diameter at harvest was compared with fruit diameter measured at individual sampling dates in order to evaluate prediction possibilities, calculate the significance of correlations and the uncertainty of prediction. The accuracy of these predictions depends on various factors and generally increases with time (Austin et al., 1999; Warrington et al., 1999). The growth analysis of fruit located on different fruiting wood (1, 2 and 3) revealed a uniform growth rate (data not presented) and therefore the position factor has been omitted from correlation analysis tests. Atay et al. (2010) have previously examined apple fruit development of several cultivars and determined that fruit growth and changes in fruit diameter are comparable within the tree. Individual cultivars were analyzed separately revealing important cultivar-specific accuracy of yield prediction. According to calculations, the correlations are statistically significant already at an early stage of apple fruit growth in all analyzed cultivars which also has purely statistical explanation – large sample sizes. The accuracy, however,

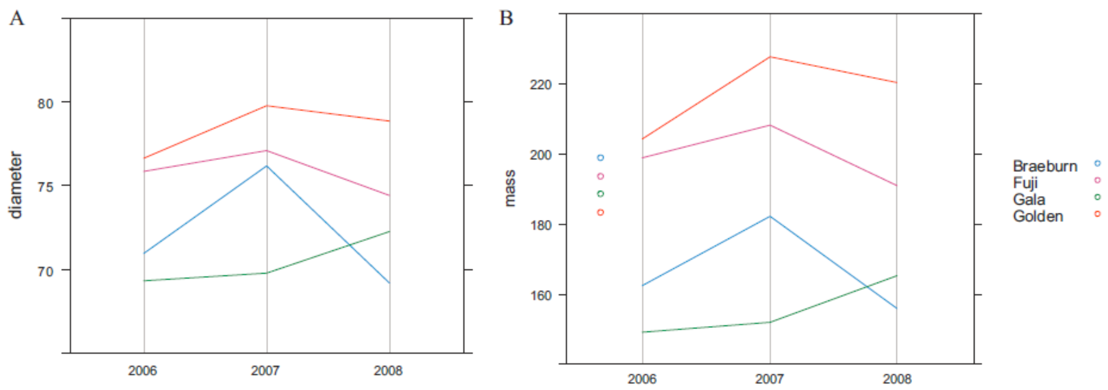

Fig. 1. Cultivar–year interaction for diameter (A) and mass (B).

Table 4
Coefficients of determination of models predicting final fruit diameter and weight in different periods during fruit development (days after full bloom) for four apple cultivars. Models are derived using data of three consecutive years 2006–2008.

Days after full bloom	Fruit diameter				Fruit mass			
	'Braeburn Hillwell'	'Fuji Kiku 8'	'Gala Brookfield'	'Golden Delicious Reinders'	'Braeburn Hillwell'	'Fuji Kiku 8'	'Gala Brookfield'	'Golden Delicious Reinders'
(21,28]	0.32	0.05	0.12	0.12	0.29	0.05	0.10	0.13
(28,35]	0.25	0.07	0.28	0.13	0.26	0.07	0.28	0.14
(35,42]	0.45	0.32	0.07	0.13	0.46	0.31	0.06	0.13
(42,49]	0.56	0.33	0.07	0.23	0.56	0.32	0.05	0.23
(49,56]	0.63	0.32	0.06	0.29	0.63	0.31	0.06	0.29
(56,63]	0.70	0.41	0.13	0.39	0.71	0.40	0.13	0.41
(63,70]	0.75	0.43	0.11	0.34	0.74	0.45	0.10	0.33
(70,77]	0.64	0.42	0.33	0.37	0.62	0.43	0.30	0.37
(77,84]	0.75	0.53	0.42	0.42	0.73	0.53	0.40	0.41
(84,91]	0.76	0.56	0.50	0.40	0.76	0.55	0.49	0.40
(91,98]	0.85	0.55	0.56	0.47	0.82	0.55	0.54	0.48
(98,105]	0.75	0.57	0.68	0.56	0.74	0.57	0.67	0.56
(105,112]	0.78	0.60	0.78	0.71	0.75	0.59	0.77	0.72
(112,119]	0.83	0.70	0.87	0.78	0.81	0.69	0.86	0.77
(119,126]	0.79	0.81	0.93	0.85	0.78	0.80	0.91	0.85
(126,133]	0.81	0.84	1.00	0.92	0.81	0.84	0.99	0.91
(133,140]	0.87	0.89	–	0.95	0.86	0.89	–	0.94
(140,147]	0.89	0.93	–	0.97	0.88	0.93	–	0.97
(147,154]	0.91	0.95	–	1.00	0.90	0.95	–	1.00
(154,161]	0.94	0.98	–	–	0.92	0.97	–	–
(161,168]	1.00	1.00	–	–	0.98	0.99	–	–

varies between early- and late-ripening cultivars (Table 4). Interestingly, the accuracy of final fruit diameter prediction of 'Fuji Kiku 8' and 'Braeburn Hillwell' cultivars was better early on in the season regardless of their late ripening pattern. Specifically in 'Braeburn Hillwell' cultivar, coefficient of determination increased steadily from 77 days after full bloom (dafb) and reached approx. 76% prediction accuracy of fruit diameter 84 dafb (Table 3). Later on (140 dafb) the coefficient of determination increased to 0.90 in 'Braeburn Hillwell' and 0.94 in 'Fuji Kiku 8' cultivars. In contrast, the accuracy of final fruit diameter prediction of the early-ripening 'Gala Brookfield' cultivar at the same time period was only 50% and reached 80% as late as 105 dafb (Table 4). Similarly, three weeks before harvest the coefficient of determination for 'Gala Brookfield' and 'Golden Delicious Reinders' cultivar increased to 0.87 and 0.95, respectively. It seems that the prediction accuracy based solely on fruit diameter measurements is sufficiently precise relatively late in apple fruit development.

Additionally, coefficient of determination between final fruit mass at harvest and fruit diameter has been calculated at selected timestamps (Table 5). Several studies report a tight connection between fruit diameter and mass for different fruit species including apple and pear (Lakso et al., 1995; Garriz et al., 1999; Marini,

Table 5
Homogeneous groups for final fruit masses of main effects and significant interactions derived using Duncan post hoc test at $\alpha = 0.05$ after factorial ANOVA.

Average weight ± standard error and homogeneous groups			
Position ($p = 0.078$)			
1	178 ± 3.9 a		
2	185 ± 3.5 a		
3	188 ± 3.9 a		
Cultivar ($p = 0.000$)			
'Golden Delicious Reinders'	217 ± 5.0 a		
'Fuji Kiku 8'	199 ± 4.2 b		
'Braeburn Hillwell'	167 ± 2.1 c		
'Gala Brookfield'	156 ± 2.7 c		
Year ($p = 0.032$)			
2007	190 ± 4.1 a		
2008	182 ± 3.4 ab		
2006	179 ± 4.0 b		
Cultivar:year interaction ($p = 0.017$)			
	2006	2007	2008
'Braeburn Hillwell'	162 ± 3.3 f	182 ± 2.9 de	156 ± 2.9 f
'Fuji Kiku 8'	199 ± 9.4 cd	208 ± 7.0 bc	191 ± 6.1 cd
'Gala Brookfield'	149 ± 4.6 f	152 ± 4.3 f	165 ± 4.6 ef
'Golden Delicious Reinders'	204 ± 8.5 bc	228 ± 9.8 a	220 ± 220 ab

1999). Results indicate a cultivar-specific correlation between the two parameters and therefore, similarly as to the accuracy of diameter prediction, early- and late-ripening cultivars differ in final mass prediction.

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2.3. MODELIRANJE PREMERA PLODOV SORTE 'GALA' ZA IZBOLJŠANJE NATANČNOSTI ZGODNJE NAPOVEDI PRIDELKA

Stajnko D., Rozman Č., Pavlovič M., Beber M., Zadravec P. 2013. Modeling of 'Gala' apple fruits diameter for improving the accuracy of early yield prediction. Scientia Horticulturae, 160: 306-312

Natančnost in pravočasnost zgodnje napovedi pridelka jabolk je odločilna za številne tehnološke in trženjske odločitve. Odstopanje klasično izvedenih napovedi od dejanskih pridelkov je tudi na velikih vzorcih pogosto zelo veliko (od –20% do +14%), na majhnih pa pogosto še veliko večje. Če želimo torej izboljšati natančnost napovedi, je potrebno izboljšati napovedovalne modele. V predhodnih raziskavi smo ugotovili, da je zanesljivost in točnost napovedovanja manjša pri zgodaj zorečih sortah. Sorta 'Gala' sodi med zgodaj zoreče in je istočasno ena najbolj razširjenih, njen delež v svetovnih sadovnjakih jablan se tudi najbolj povečuje. Jasno je, da je izboljšanje napovedi pridelka prav pri tej sorti zelo pomembno. Variabilnost zanesljivosti napovedi je lahko odvisna tudi od obloženosti dreves (gostota oveska plodov). Da bi dosegli izboljšanje natančnosti napovedi, smo izvedli meritve priraščanja plodov v treh zaporednih letih (2009, 2010, 2011) na različno obloženih drevesih nasada sorte 'Gala' na lokaciji Sadjarski center Maribor. Z uporabo teh meritev v modelni kalkulaciji po Gompertzu smo poskušali izboljšati modelne parametre in povečati zanesljivost napovedi. Ugotovili smo, da se modelni parametri sicer odzovejo na različne obremenitve dreves, nismo pa zabeležili razlik v končni velikosti in masi plodov. Na različne obremenitve se najbolj odziva parameter β, ki določa, kako močno bo rast plodu upadla, ko ta doseže največje povečanje svoje mase. V prihodnje bo raziskovalno pozornost potrebno posvetiti prav velikosti parametra in razlogom za njegovo spreminjanje. Povprečni, sedaj veljavni napovedovalni model, nam je v dveh od treh let dal 95% natančnost napovedi. Z uporabo korigiranih parametrov smo zelo izboljšali tudi napoved v letu, ko povprečni model ni zadovoljil pričakovanj.

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Modeling of 'Gala' apple fruits diameter for improving the accuracy of early yield prediction

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ABSTRACT

A long-term growth curves usually describes the development of fruits insufficiently for a particular season hence it might cause severe discrepancies between the forecasted and harvested characteristics. For improving the early yield forecasts of 'Gala Schniga'/MM9 apples (Malus × domestica Borkh) the diameter of fruits on different abounded trees; low (L) 4 fruits/cm^2, medium (M) 7 fruits/cm^2 and high (H) 9 fruits/cm^2 was measured in three successive growing seasons (2009, 2010 and 2011) every two weeks from the T-stage till picking fruits. The fruits' development was observed on the terminal (TL), 2-years (2L) and 3-years old shoots (3L). The input data were transformed over natural logarithm and regression analyzes into modified Gompertz function (models) describing the fruit growth on different abounded trees and different position of shoots on the trees. The use of specific models improves annual yield forecasts of 28 commercial 'Gala' orchards over the long-term model significantly. On that way the minimal difference of 200 kg/ha was calculated with middle-loaded 2L model in 2009, 510 kg/ha with low-loaded TL model in 2010 and 156 kg/ha with middle-loaded 3L model in 2011, respectively.

1. Introduction

Apple production suffers from alternate bearing, which leads to temporal variation in fruit yields as well as fruit quality on individual trees (Noguchi et al., 2003). The position of the fruits in the canopy and the interaction with other tree neighboring structures additionally affect fruit growth and development (McArtney et al., 1996; Lauri and Lespinasse, 1999). However, the yield per tree has shown almost linear relationships to the number of fruit per plant, independently of the rootstock (Elfving and Schechter, 1993). From all those reasons the challenge for fruit growers and researchers was to determine annual harvest of apples as accurately as possible, because it is essential for the organization of harvesting and storage of harvested crops, and pricing. Thus modeling of fruit growth with an emphasis on tree variability was a crucial step in the management of fruit quantity and quality for decades (Hester and Cacho, 2003) with a great impact on yield prediction per hectare in every growing region. However, all older models simulate the environmental conditions in the orchard, which can significantly vary from the real values.

On the other side, the prediction based on heat accumulation, which is calculated as the sum of the daily minimum and the maximum temperature from the date of full flowering to harvest shows to be relative successful tool (Streif, 1996; Stanley et al., 2000). Moreover, due to the evolutionary behavior of the biological individuals and assumption-dependent non-linear characteristics, models are valid in only a limited condition range and time frame (Verdenius and Broeze, 1999). On the other hand, more advanced piecewise power function and spline exponential function promised sufficient accuracy for predicting fruit mass from the fruit diameter (De Silva et al., 1997).

Besides, apple fruit modeling represents very important tool for early yield prediction required by the orchardists, retailers and planners of cooling capacities. Since in the European Union (EU-25), about 10 million tons of apples are harvested every year (FAOSTAT, 2011), accurate yield prediction has to be obtained before the annual Prognosfruit convention in the first decade of August (WAPA, 2012), which represents quite a challenge for researches. In the last decades, in the fruit forecast electronic field data capture has become widely adopted as a result of advances in computer technology, which led Stajnko et al. (2004, 2009) to develop a system for capturing images of the tree and subsequent automatic processing of images. Such data acquisition enables capturing of many samples of different apple and pear varieties at various farmers in a short time in order to improve forecast accuracy. However, for reaching 95% accuracy expected from the fruit growing chain, it is desirable to predict the fruit size via simulation models of growing curves as accurately as possible, since it is directly connected to the fruit mass.

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The aims of the present paper are: (1) to describe the within-tree variation in size and growth of fruit in apple trees of cultivar 'Gala Schniga' in three successive growing years 2009–2011; (2) based on this information the models of growing curves are designed and compared with the long-term curve commonly applied for forecasting the yield of 'Gala' apples: (3) to compare the actual measured apples with the models' values; (4) to represent the accuracy of forecasting the yield with different models on 48 commercial 'Gala' Slovenian orchards.

2. Materials and methods

2.1. Experimental design

Data for the analysis of within-tree variation came from a branch-mapping study conducted on twelve spindle trained 6-year-old 'Gala Schniga' apple trees grafted on M9 rootstock and planted at 3.2 m × 0.7 m north–south oriented rows.

The experiment was carried out during 3 successive growing seasons 2009, 2010 and 2011 in the research orchard of Fruit Center Maribor–Gačnik (46°37′49″ N, 15°40′50″ E), owned by the Slovene Chamber of Agriculture and Forestry.

In the winter of 2009, twelve trees were selected that were uniform in the number of branches, TCSA and canopy volume. The trees were assigned to three levels of fruit crop i.e. low-loaded trees (4 fruits/cm^2 TCSA), middle- loaded trees (7 fruits/cm^2 TCSA) and high-loaded trees (9 fruits/cm^2 TCSA) measured at the insertion point of the first productive structure. For each replication four trees were selected per treatment. On each Tree 10 fruits were selected from different braches i.e. 3 from terminal, 4 from 2-years old branches (spur) and 4 from 3-years old branches (axially). The distribution of fruit types in each of the four trees was similar and evenly distributed across levels over the tree crown. Crop loads were established through manual fruit tinning in each of the three successive seasons.

2.2. Assessments of the fruit physical characteristics

Since the same fruits had to be measured during the whole growing season, the mass of each fruit was estimated through the fruit equatorial diameter. The maximum diameters of individual tagged fruits were measured non-destructively every 14-days started 3 weeks after T-stadium corresponding to 40, 55, 61, 75, 89, 104, and 126 days after full bloom (DAFB) using a digital caliper Prowin, HMTY0006. The pickup time was determined by using the Streif Index (Streif, 1996). At harvest, all the fruits from each tree were weighted individually by using a digital balance (Mettler PM 460) and classified to 1st and 2nd grade according to 70 mm diameter and 50% red color threshold.

2.3. Fruit mass modeling

The fruit mass of 'Gala' was estimated from the diameter non-destructively based on a transformation of power function developed by Mitchell (1986) and Welte (1990):

$$W = A \cdot d^B \qquad (1)$$

where, W = mass (g), A = 0.4059, d = equatorial diameter (cm), B = 2.9602.

For determining the fruit growing curve a modified Gompertz function procedure described by Welte (1990) and Stanley et al. (2000) was applied, which has got the following form:

$$D(t) = 3.5 + \alpha \cdot (1 - e^{-\beta t})^{\gamma} \qquad (2)$$

where, $D(t)$ = fruit diameter (mm), t = time after the full blossom till harvest (days), $\alpha + 3.5$ = maximal theoretical fruit diameter (mm), β, γ = parameters concerning the fruit shape.

The procedure for estimating α, β and γ is described in detail by Welte (1990) and is based on the linear regression estimation between the natural logarithm of the fruit diameter and natural logarithm of days after full blossom. From the ANOVA table of the regression estimation α is calculated as the inverse value of natural logarithm of given coefficient of intercept, β is given as standard error of intercept and γ is given as coefficient of depended variable. This function was validated each time using 16 fruits from adjacent plants on the sampling date, which gave coefficients of determination from 0.97 to 0.99.

2.4. Weather data

Meteorological data between the full bloom and the harvest were obtained from the weather station 'Gačnik', owned by Ministry of Agriculture, Forestry and Fisheries of Slovenia. The data collected included global radiation, MJ m^{-2} (Pyranometer SP-lite); heat accumulation in °C calculated as the sum of daily minimum (Tmin) and maximum temperatures (Tmax) (sensor 50YA); precipitation (mm) at 1.5 m in the morning (08:00); maximum precipitation (mm) (sensor Rain-O-Matic) average of minimum and maximum daily relative humidity (sensor 50YA), %; surface wetness (sensor A730WET).

2.5. Yield forecast

The yield of 28 commercial 'Gala' orchards, which differ according to the growing system and age (Table 1) was forecasted by the method of image analysis, which was described in detail by Stajnko et al., 2009. In the original algorithm the long-term equation (α = 80.676, γ = 2.1218, β = 0.0384) was replaced with all nine different models for particular growing season according to three different fruit loads and fruit position on the tree and tested on the accuracy of early yield forecast.

2.6. Statistical analysis

Once the growing equitation for 'Gala' apple was determined for each season and the position on the tree, the fruit mass was estimated for all models. Then the estimated data were compared with the measured data with the paired sampled test (t-test, $p \leq 0.05$) with a statistical package IBM SPSS Statistics 21.0 program.

Table 1
Orchards included in forecasts according to growing form and year of planting.

Number of orchards	Planted < 1995		Planted 1995–2004		Planted > 2006	
	Spindle	Super spindle	Spindle	Super spindle	Spindle	Super spindle
28	1	4	3	9	1	10

Table 2
The average temperature and precipitations in the growing period of 'Gala' apples in 2009–2011.

	Average temperature [°C]			Heat accumulation [°C]			Precipitation [mm]		
Month	2009	2010	2011	2009	2010	2011	2009	2010	2011
May	16.6	15.1	15.6	1090.5	969.1	996.2	78.1	80.7	95.4
June	17.5	19.1	19.0	1088.1	1167.2	1167.3	160	97.1	137.8
July	20.8	22.2	19.6	1349.4	1429.6	1239.4	151.5	89.2	145.7
August	20.7	19.1	20.9	1358.0	1250.7	1331.6	306.8	172	56.9
September	16.8	13.5	18.3	1099.8	862.6	1178.4	67.5	238.1	65.4
Sum				5985.8	5679.2	5912.9	763.9	677.1	501.2

3. Results and discussion

3.1. Fruit diameter growth

In all seasons the treatments with the low-loaded trees bear fruits with a significantly higher mass than on the trees with the medium- and high-loaded treatments (Figs. 1–3, and Tables 3–5). These findings are similar to Yuria et al. (2011), who detected the lowest yields in low laods and no differences between the medium and high crop loads.

The number of days from full blossom to harvest differed from year to year, so the fruits' growth lasted only 122 days in 2009, 129 days in 2010 and 132 days in 2011, respectively.

The length of the growing season and consequently the harvesting date assumed to be significantly connected with the heat accumulation in May, which might be explained by more intense cellular division (Goffinet et al., 2005), allowing for greater growth potential during the entire season. On the other side the lack of precipitation in June and July 2010 seemed to slow the growing of apples and subsequently prolonged the growing season.

The absolute growth rate (mm day^{-1}) was increasing till approximately 45 DAFB and then slowly decreasing till the harvesting in all three crop loads in all three seasons (2009–2011), but it was special for each year (Figs. 4–6).

The different crop-load affected the dynamics of fruit growth differently. In 2009 (Fig. 4) the highest increase of diameter (0.79 mm day^{-1}) was measured on 39 DAFB for the medium and high-loaded trees and 0.78 mm day^{-1} for low-loaded trees, respectively. In 2010 (Fig. 5) the highest increase of diameter (0.96 mm day^{-1}) was measured nine days earlier, on 30 DAFB for the low-loaded trees, 0.93 mm day^{-1} for middle-loaded and 0.90 mm day^{-1} for the low-loaded, respectively. In 2011 (Fig. 6) the highest increase of diameter (0.76 mm day^{-1}) was estimated on 68 DAFB for the low- and medium-loaded trees and 0.80 mm day^{-1} for high-loaded trees, respectively.

The highest absolute fruit growth corresponded very close to the heat accumulation (Table 2), calculated as the sum of the daily minimum and the maximum temperature in May and not from the date of full blossom to harvest as suggested by Streif (1996), Perry et al. (1987), Stanley et al. (2000). On the other side, more rainfall than average in June and July 2009 as well in 2011 might decrease the light emissions and subsequently the photosynthesis efficiency.

The relative diameter growth (mm day^{-1} mm^{-1}) showed similar trend as the absolute growth in all experimental years. The biggest variations as well the maximum values of daily diameter growth were estimated at the begging of experiment till 50 DAFB due to the intense cellular division and thinning. However, later on after approximately 60 DAFB a slighter falling tendency was estimated, which persisted at approximately 0.008 mm day^{-1} mm^{-1} till the harvest.

3.2. Fruit modeling

Tables 3–5 showed estimated (modeled) and measured fruit diameter as well estimated and weighted fruit mass, which differed

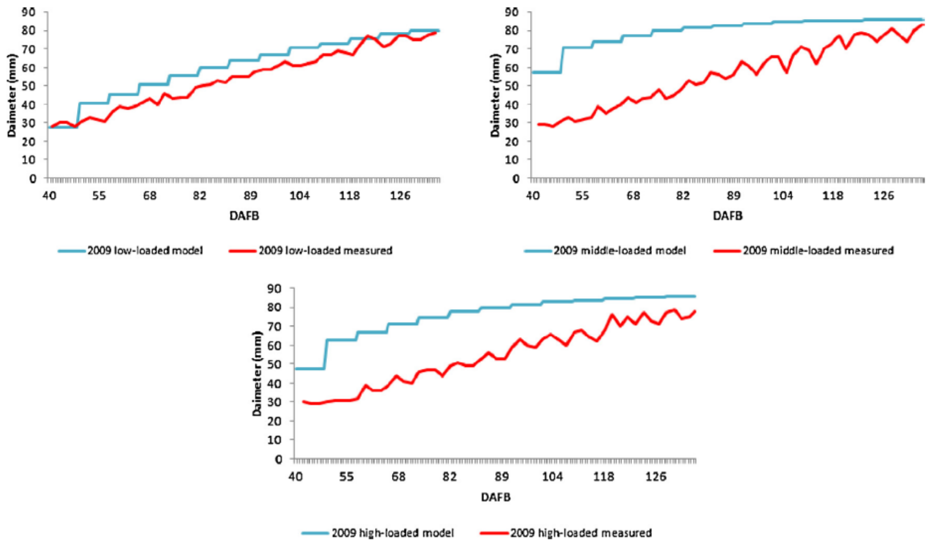

Fig. 1. Comparison between measured and modeled growing curves of 'Gala' apples at different crop loads in 2009.

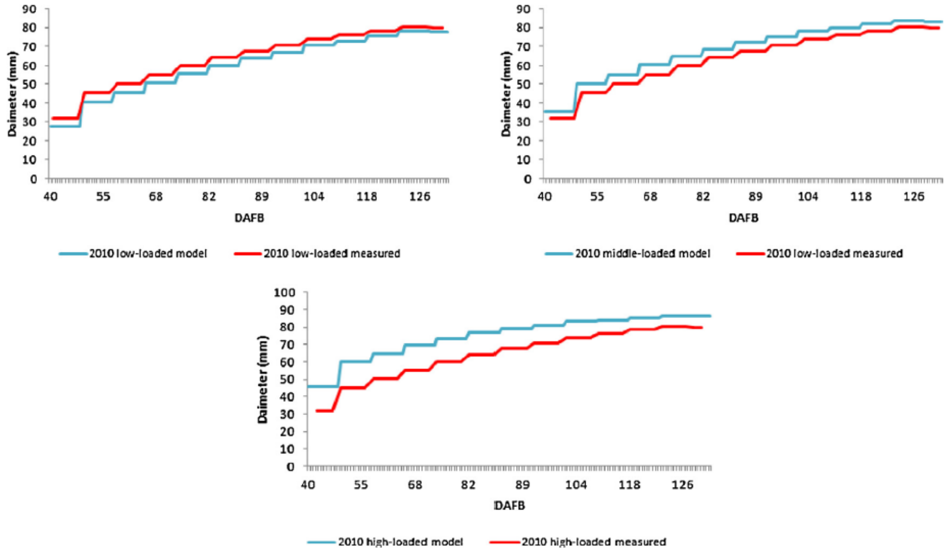

Fig. 2. Comparison between measured and modeled growing curves of 'Gala' apples at different crop loads in 2010.

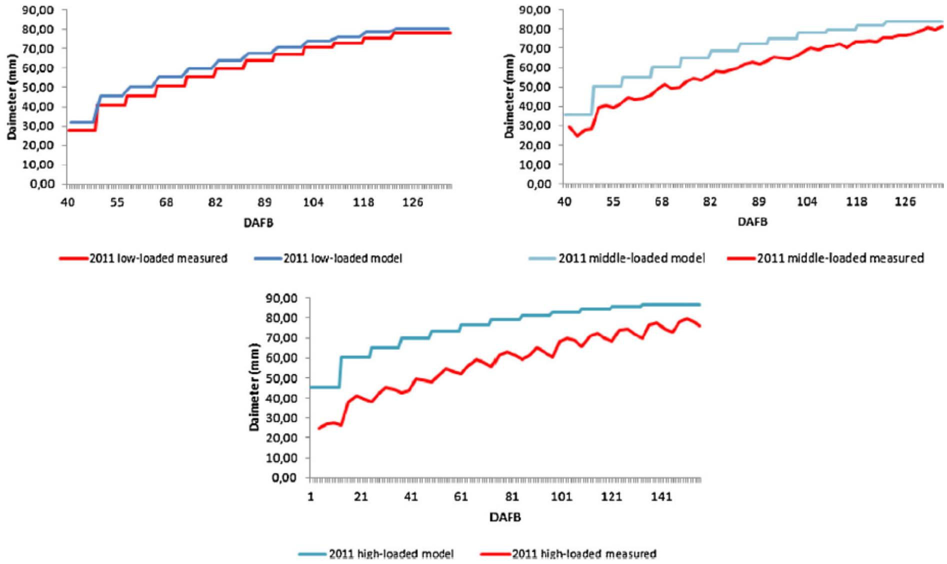

Fig. 3. Comparison between measured and modeled growing curves of 'Gala' apples at different crop loads in 2011.

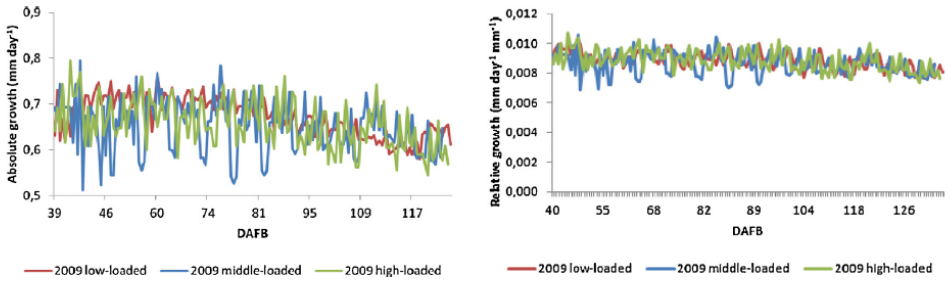

Fig. 4. Absolute (left) and relative (right) fruit diametre growth of 'Gala' apples under three crop loads in 2009.

Table 3
Estimated and measured fruit characteristics in 2009 according to different fruit load.

Fruit growing period 18th April–18th August 2009	Weighted fruit		Estimated fruit		Model parameters		
Bloom/fruit position	Diameter (mm)	Mass (g)	Diameter (mm)	Mass (g)	α	γ	β
Low-loaded							
Terminal	84.35	224	85.99	237	85.80	2.124	0.032
2-years shoot	86.16	238	91.56*	285*	88.15	2.164	0.061
3-years shoot	86.25	239	87.87	253	84.61	2.097	0.053
Middle-loaded							
Terminal	78.38	180	75.74	163	72.24	1.848	0.240
2-years shoot	82.69	211	83.54	217	80.16	2.075	0.058
3-years shoot	82.16	207	82.10	207	78.73	2.093	0.057
High-loaded							
Terminal	85.93	236	87.35	248	84.10	2.283	0.053
2-years shoot	83.38	216	84.29	223	80.80	2.199	0.085
3-years shoot	86.48	241	91.29*	283*	87.79	2.378	0.104

* Significant difference between estimated and weighted at $p < 0.05$ (Duncan test).

Table 4
Estimated and measured fruit characteristics in 2010 according to different fruit load.

Fruit growing period 27th April 2nd September 2010	Weighted fruit		Estimated fruit		Model parameters		
Bloom/fruit position	Diameter (mm)	Mass (g)	Diameter (mm)	Mass (g)	α	γ	β
Low-loaded							
Terminal	78.8	183	78.19	179	75.19	1.762	0.045
2-years shoot	79.42	187	79.60	188	76.10	1.780	0.087
3-years shoot	79.61	189	79.28	186	75.79	1.772	0.076
Middle-loaded							
Terminal	78.81	183	79.97	191	87.27	2.222	0.023
2-years shoot	81.79	204	83.28	215	88.23	2.184	0.025
3-years shoot	83.81	220	86.23*	239*	86.31	2.218	0.032
High-loaded							
Terminal	79.87	190	81.21	200	77.71	1.916	0.121
2-years shoot	77.93	177	78.38	180	74.89	1.729	0.079
3-years shoot	78.81	183	82.16*	207*	78.73	1.832	0.061

* Significant difference between estimated and weighted at $p < 0.05$ (Duncan test).

Table 5
Estimated and measured fruit characteristics in 2011 according to different fruit load.

Fruit growing period 17th April 26th August 2011	Measured fruit		Estimated fruit		Model parameters		
Bloom/fruit position	Diameter (mm)	Mass (g)	Diameter (mm)	Mass (g)	α	γ	β
Low-loaded							
Terminal	82.43	209	86.23*	239	88.23	2.286	0.021
2-years shoot	81.99	206	83.26	215	88.23	2.184	0.025
3-years shoot	78.87	183	77.51	174	86.31	2.218	0.032
Middle-loaded							
Terminal	79.88	190	85.77*	235	83.10	2.312	0.044
2-years shoot	82.17	207	83.39	216	84.43	2.25	0.03
3-years shoot	83.95	221	85.73	235	82.27	2.521	0.07
High-loaded							
Terminal	81.23	200	82.86	212	84.18	2.40	0.036
2-years shoot	84.29	223	86.26	239	83.67	2.26	0.043
3-years shoot	83.05	214	85.36	232	81.94	2.524	0.064

* Significant difference between estimated and weighted at $p < 0.05$ (Duncan test).

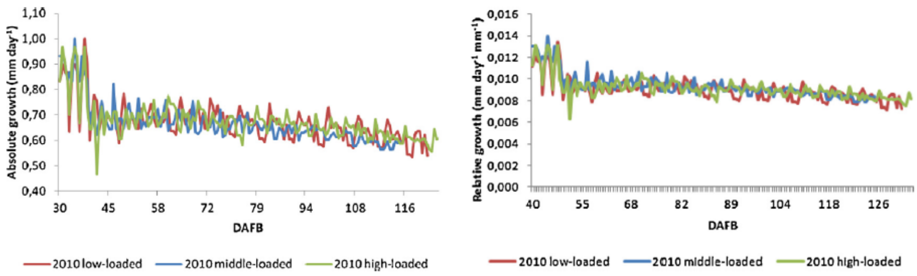

Fig. 5. Absolute (left) and relative (right) fruit diametre growth of 'Gala' apples under three crop loads in 2010.

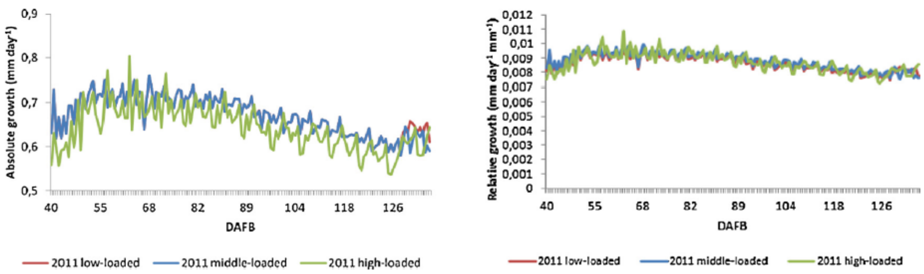

Fig. 6. Absolute (left) and relative (right) fruit diametre growth of 'Gala' apples under three crop loads in 2011.

significantly from year to year on all tree loads and fruit (bloom) positions. In 2009 the mass as well the diameter of fruit was estimated accurately except on 2-years shoots low-loaded trees and 3-years shoots high-loaded trees; in 2010 on 3-years shoots and 3-years high-loaded trees. Contrary, in 2011 a Terminal low-loaded model and Terminal middle-loaded model overestimated the fruit diameter as well the fruit mass. The reason in variation of model accuracy across different tree loads and years might be affected by the intra trees variations, since there was always the same number of fruits on the same trees each year.

On average the highest fruit mass was measured in 2009 (221 g), followed by 191 g in 2010 and 206 g in 2011. It is assumed that the fruit mass was dominantly affected by the May temperatures as already stated by Stanley et al. (2000), and probably by the lack of precipitations in June–July since there was used no additional irrigation in our experimental orchard.

3.3. *The accuracy of modeling the fruit growing*

As seen from Tables 3–5, the increase in fruit load affected α, γ, β parameters of the fruit growth curve functions for all experimental years differently. A general view showed the decrease of α parameter with increasing of fruit load as well the bloom position, whereby α was the lowest on a high-loaded trees and the 3-years shoots. This is logical connection, because α predicts the maximal fruit diameter. On the other side γ, β parameters indicated the steepness of the curve i.e. the speed of the growing and ripening, which is seen only for γ parameter in case of the shortest-growing season 2009 and the longest 2011, respectively.

The deeper analysis of particular models showed for 2009 (Table 3) significant difference between measured and estimated diameter and mass for all position and fruit load except for 2-years and 3-years shoots on middle-loaded trees fruit loads except for 3-years shoot on low-loaded trees. In 2010 (Table 4) insignificant difference between measured and estimated diameter and mass was detected only for the model 'Terminal shoots on middle-loaded trees' and '2-years shoots on high-loaded trees'. Table 5 represents three models describing the estimated fruit mass and diameter of 'Gala' apple at different fruit load in 2011, which again shows significant difference between measured and estimated diameter as well the mass for all fruit loads except for '3-years shoot on low-loaded trees'.

Table 6
Average forecasts and harvested yields from 2009 to 2011 for different varieties models of fruit growth.

	Models	Position	Forecast (kg/ha)	Harvest (kg/ha)	Difference H/F
2009	Long-term equation		19.531	20.573	−1.042*
	Low-loaded	Terminal	21.987	20.573	1.414*
		2-years	22.245	20.573	1.672*
		3-years	21.473	20.573	900
	Middle-loaded	Terminal	19.673	20.573	−900
		2-years	20.773	20.573	200
		3-years	18.387	20.573	−2.186*
	High-loaded	Terminal	19.416	20.573	−1.157*
		2-years	18.644	20.573	−1.929*
		3-years	19.287	20.573	−1.286*
2010	Long-term equation		34.653	27.212	7.441*
	Low-loaded	Terminal	27.722	27.212	510
		2-years	29.253	27.212	2.041
		3-years	28.913	27.212	1.701
	Middle-loaded	Terminal	29.593	27.212	2.381*
		2-years	33.505	27.212	6.293*
		3-years	37.076	27.212	9.864*
	High-loaded	Terminal	30.954	27.212	3.742*
		2-years	27.892	27.212	680
		3-years	32.144	27.212	4.932*
2011	Long-term equation		29.900	30.344	−444
	Low-loaded	Terminal	30.900	30.344	556
		2-years	27.935	30.344	−2.409*
		3-years	22.519	30.344	−7.825*
	Middle-loaded	Terminal	30.644	30.344	300
		2-years	28.077	30.344	−2.267*
		3-years	30.500	30.344	156
	High-loaded	Terminal	27.507	30.344	−2.837*
		2-years	31.070	30.344	726
		3-years	30.070	30.344	−274

* Significant difference between estimated and weighted at $p < 0.05$ (t-test).

3.4. The accuracy of forecasting the yield

Table 6 shows the average forecasted and harvested yield of 28 'Gala' apple orchards included in the annual prediction of apple yield in Slovenia from 2009 to 2011. Firstly, for each year the long-term model based forecast is represented and then all nine annually specific models.

For 2009 the model 'middle-loaded, 2-years shoot' was proved to forecast the yield most accurately, since the difference between estimated and harvested yield was on the average only 200 kg/ha. On the other side the long-term model underestimated the yield for 1.042 kg/ha, which is also significantly higher than by the second best models 'low-loaded, 3-years shoot' and 'low-loaded, 2-years shoot', respectively.

In 2010 the long-term model overestimated the yield on average for 7.441 kg/ha, which was the second poorer forecast after 'middle-loaded 3-years shoot'. However, by the use of specific annual models 'low-loaded, terminal' (+510 kg/ha) and 'high-loaded, 2-years shoot' (+680 kg/ha) the accuracy of the forecast was improved significantly.

On the other side, in 2011 the use of the long-term model underestimated the yield on average only for 444 kg/ha, which means that this particular year was almost 'the average'. Still models 'middle-loaded, 3-years shoot' (156 kg/ha) and 'high-loaded 3-years shoot' (−247 kg/ha), estimated the yield significantly better, which means that also in average yield the accuracy depended on the type of models.

4. Conclusions

The proposed modeling of 'Gala Schniga'/MM9 apple growth levels based on 14-days measuring interval showed significant difference between different fruit-loads as well growing seasons. The selected procedure with a modified Gompertz function overestimated the diameter at harvest in particular fruit-loads, thus also the estimated fruit mass calculated by power function differed from the measured values.

Despite of smaller deviations in fruit mass of particular models their application in forecasting the yield of 28 commercial 'Gala' orchards showed significant improvement of annual forecasts in comparison to the long-term model due to (i) specific annual temperature and precipitation development, which affected the growing of fruits specifically from year to year and (ii) mixed crop-loads which is commonly used in commercial orchards, which cannot be described accurately enough by a specific fruit position model.

However, further work is needed to study more advanced equations such as a three-parameter piecewise power function and a five-parameter spline exponential function, which fits the data even better. When fully developed, newer models are expected to be spread for forecasting the yield of other varieties in commercial orchards even more precisely.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.scienta.2013.06.003.

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3 RAZPRAVA IN SKLEPI

3.1 RAZPRAVA

V prvem poskusu smo se osredotočili na spremljanje povečevanja premera plodov pri štirih pomembnih sortah žlahtne jablane (*Malus domestica* Borkh.): 'Gala' Brookfield®, 'Zlati delišes' Reinders®, 'Fuji' Kiku® in 'Braeburn' Hillwel®. Z raziskovalnega zornega kota so pomembne predvsem fenološke in pomološke razlike med sortami.

Za način spremljanja smo izbrali edino znano nedestruktivno in dokaj hitro izvedljivo metodo – merjenje ekvatorialnega premera plodov. Le s takim načinom merjenja zagotovimo ponovljivost meritev na istih plodovih. Da bi se izognili napakam zaradi mogoče nesimetričnosti plodov, smo premer vsakega plodu izmerili dvakrat z zamikom za 90^0 in zabeležili povprečno vrednost. Principa merjenja na istih plodovih skoraj ni mogoče zagotoviti pred končanim naravnim in tehnološkim redčenjem plodičev. Šele po 29. dnevu po polnem cvetenju (29 DAFB), ko je prvi vrh naravnega trebljenja plodičev (Jakopič in sod., 2015), je smiselno merjene plodove označiti in jih pričeti meriti. Ta datum običajno sovpada tudi s t. i. T-stadijem. T-stadij je opisan kot dan, ko pecelj plodu in tangenta na obodu plodu v točki dotikanja oblikujeta videz črke T (Blanke in Kunz, 2009). Meritve smo nato opravljali v intervalih 5–7 dni, vse do tehnološke zrelosti plodov in obiranja. Plodov, ki so v času od označitve do obiranja odpadli, nismo nadomestili z novimi. V povprečju vseh sort in let smo na ta način izgubili le 14,4 % označenih plodov, kar potrjuje trditve številnih avtorjev, da večina plodičev odpade do 30 DAFB in 95 % vseh do 60 DAFB (Magein, 1989).

Podatke o datumih meritev in izmerjene vrednosti smo uredili v Excelovi datoteki. Premer plodov smo v statistični obdelavi podatkov vzeli za parameter rasti in odvisno spremenljivko, čas pa kot neodvisno spremenljivko. Čas smo normalizirali v podatek – dnevi po polnem cvetenju (DAFB).

Ob analizi podatkov iz prvega poskusa smo se najprej osredotočili na vprašanje, ali je tako zapleten proces kot je priraščanje plodov sploh mogoče z zadovoljivo zanesljivostjo modelno napovedovati. Če bi bilo namreč priraščanje močno odvisno od zunanjih dejavnikov, na katere nimamo pomembnega vpliva, bi bila vsakršna napoved, še prav posebej dolgoročna, zelo nezanesljiva.

Za opisovanje vzorca priraščanja individualno merjenih plodov smo uporabili negativni eksponentni model. Kot je dokazal von Bertalanffy (1938), je to teoretično pravilna enačba za opisovanje izometrične rasti ob uporabi enodimenzionalnega rastnega parametra – v našem primeru je to premer plodu. Izrisane krivulje priraščanja plodov pri vseh sortah in v vseh opazovanih letih kažejo tipično negativno eksponentno obliko in so med sortami in leti dokaj podobne. Od ocenjevanih dejavnikov je dejavnik položaja plodu (na enoletnem poganjku terminalno, na brstiču dvoletnega lesa, na brstiču ali brstiki 3 letnega lesa) brez vpliva na priraščanje plodov in smo ga zato izključili iz nadaljnjih analiz. V uporabljeni von Bertalanffyjevi enačbi (enačba …1) so pomembni trije faktorji:

ϕ 1 – parameter opisuje asimptoto krivulje (potencialno končno velikost plodu v mm)

ϕ 2 – parameter določa naklon krivulje (se navezuje na stopnjo priraščanja v mm/dan)

ϕ 3 – parameter določa presečišče krivulje z osjo x (v dneh)

Parametri, ki smo jih določili za vse sorte in vsa leta, kažejo naslednje vrednosti (srednje vrednosti in 95% interval zaupanja):

ϕ 1: 93,5 (92,2–94,8)

ϕ 2: –4,43 (–4,46 do –4,41)

ϕ 3: 9,2 (8,75–9,65)

Koeficient determinacije r^2 povprečnega modela je 91,3 %. Parameter ϕ 3 je za naš primer nepomemben. Določa namreč presečišče krivulje z osjo x in pravzaprav le pomika krivuljo rasti v smeri osi x. V raziskavi modeliranja vzorcev priraščanja na Univerzi Cornell, Geneva, USA so v ekspolinearnem modelu priraščanja mase plodov začetni eksponentni del krivulje v približno prvih 30 DAFB označili kot »lost time« – natančno ga opredeli projekcija presečišča linearnega dela krivulje z osjo x (Lakso in sod., 1995). Ker pa smo meritve začeli po T-stadiju, nimamo za ta čas relevantnih meritev, torej tega dela krivulje ne obravnavamo.

Parameter ϕ 1 (potencialna končna velikost plodu) je statistično značilno odvisen od sorte, ni odvisen od leta, zanj je potrjena šibka interakcija med sorto in letom. To nakazuje, da je z modelom napovedana končna velikost plodu (opisana kot asimptota krivulje) genetsko nadzorovana (vodena) in nanjo le zmerno vplivajo drugi notranji (položaj plodu) in zunanji (vpliv leta – vreme) analizirani dejavniki. Če natančneje pogledamo potek tega parametra po sortah, ugotovimo, da je razlika med napovedano končno velikostjo plodu in dejansko izmerjeno končno velikostjo plodu največja pri sorti 'Gala' in da je tudi delež pojasnjene variance najmanjši (r^2 = 0,37). Nekoliko bolje je pri sorti 'Braeburn' (r^2 = 0,49) in sorti 'Zlati delišes' (r^2 = 0,67). Najbolje je pri pozno zoreči sorti 'Fuji '(r^2 = 0,75). Tudi drugi avtorji poročajo o večjem odstopanju med napovedano in realizirano končno velikostjo plodov pri zgodnejših sortah (Atay in sod., 2010; Ozkan in sod., 2012). Dokaj verjetno je predvidevanje, da zgodnje sorte dosežejo tehnološko zrelost relativno zgodaj v svojem razvojnem obdobju in bi se njihova rast plodov še nadaljevala tudi po doseženi tehnološki zrelosti. Posebej očitno je ta vpliv viden pri sorti 'Gala' v letu 2006, ko poteka krivulja priraščanja skoraj linearno. Tudi sicer avtorji to sorto in njene klone opisujejo kot zelo odzivne na temperaturo, lokacijo in druge okoljske dejavnike (Warrington in sod., 1999).

Dobro prileganje dejanskih meritev zgornji asimptoti pri pozno zorečih sortah 'Fuji' in 'Braeburn' opisujejo tudi drugi avtorji (Talaie in sod., 2011). Kljub vsemu pa moramo naravni rastni potencial ali teoretično pričakovano končno velikost plodov posamezne sorte (parameter ϕ 1) vendarle razlikovati od realno dosežene končne velikosti plodov. Modelne napovedi namreč zmeraj opisujejo rast v optimalnih razmerah, kar pa v resničnosti pogosto ni tako (Lakso in sod., 1995). Pojasnjevanja priraščanja plodov z modelnimi pristopi so zaradi medsebojno odvisnih povezav med zunanjimi dejavniki in končno maso obranih plodov sicer težavna (Welte, 1990; Lakso in sod., 1995), a vsi se strinjajo, da so za povečevanje premera plodov najpomembnejši notranji dejavniki (genske omejitve), podobno kot kažejo rezultati našega modela. Pomembna ugotovitev naše raziskave je tudi ta, da imajo zgodaj zoreče sorto večjo razliko med napovedano in dejansko končno velikostjo plodov kot pozno zoreče sorte.

Parameter ϕ 2, ki določa naklon krivulje, pokaže stopnjo priraščanja analizirane sorte. Tukaj so se statistično potrdile razlike med sortami in leti, ni pa bilo interakcije med njimi. Sorte 'Gala', 'Zlati delišes' in 'Fuji' priraščajo podobno, med njimi ni statistično značilnih razlik. Počasnejše priraščanje je značilno za sorto 'Braeburn'. Do podobnih rezultatov so v svoji raziskavi prišli tudi Atay in sodelavci (2010), ko so primerjali sorte 'Jersaymac', 'Gala' in 'Braeburn'. V tej zvezi je pomembno omeniti raziskavo o vplivu različnih temperatur v zgodnji razvojni fazi (10–40 in 40–80 DAFB) na zgodnje priraščanje plodov. Sorta 'Braeburn' je pokazala v vseh temperaturnih režimih največje dnevne priraste plodov. Lastnost sorte 'Braeburn', ki tudi v neugodnih temperaturnih razmerah obdrži dobre priraste plodov, pojasnjuje iz pridelave znano dejstvo, da ima ta sorta, za razliko od sort 'Gala' in 'Zlati delišes', plodove primerne velikosti tudi v pridelovalnih območjih s hladnejšo klimo (Warrington in sod., 1999).

Priraščanje plodov v fazi od T-stadija do zorenja, ki ga v večjem delu tega obdobja popiše parameter ϕ2, je lahko prvenstveno pripisano vakuolizaciji celic, povečevanju celic ter razvoju medceličnih prostorov (Warrington in sod., 1999). V tem času več avtorjev ta proces opiše kot linearno priraščanje (Atay in sod., 2010). To lahko pripišemo konstantnemu prestrezanju svetlobe v krošnji, ki je v tem času dosegla končni volumen (Goudriaan in Montheith, 1990). Priraščanje plodov v tej fazi (faza povečevanja celic) je torej enakomerno in tudi najpomembneje vpliva na končno velikost plodov, saj v povprečju traja 15–16 tednov. Pozno v sezoni priraščanja zaznamo zmanjševanje prirasta (Lakso in sod., 1995). Plodovi jabolk, analizirani v našem poskusu, kažejo prav takšen potek priraščanja. Najprej kažejo linearno priraščanje premera, ki mu sledi upočasnjeno priraščanje v zadnji fazi rasti plodov nekaj tednov pred doseženo tehnološko zrelostjo. Zanimivo je, da se pri sorti 'Gala' linearno priraščanje konča šele nekaj dni pred doseženo tehnološko zrelostjo.

Na podlagi naših rezultatov lahko sklepamo, da je negativna eksponentna oblika priraščanja univerzalna za sorte jabolk v enakih razmerah za čas od T-stadija do tehnološke zrelosti – linearno povečevanja premera plodov, ki mu sledi upočasnjeno priraščanje v zadnji fazi rasti. Zanimivo je, da zgodaj zoreče sorte kot je 'Gala', ki je bila analizirana v našem poskusu, karakterizira relativno linearno priraščanje debeline plodov skoraj do dosežene tehnološke zrelosti in obiranja.

Ugotovili smo torej, da na končno velikost plodov vplivata parametra ϕ 1 in ϕ 2 ter da sta v statistično značilni zvezi s sorto (genetske lastnosti), parameter ϕ 2 pa tudi z letom. Da bi bolje opisali značilnosti let v opazovanem obdobju (2006–2008), smo iz meteoroloških podatkov za lokacijo pridelave (Sadjarski center Maribor) pripravili povzetke nekaterih pomembnih vremenskih in fenoloških spremenljivk. Po trditvah večine avtorjev ima na priraščanje plodov največji vpliv temperatura, še posebej temperatura v zgodnji razvojni fazi 0–40 DAFB (Tromp in sod., 2005). V tem obdobju se zgodi tudi največ mejnikov v fiziološkem razvojnem času plodov: oprašitev in oplodnja, celične delitve, največje absolutno priraščanje plodov, največje relativno priraščanje plodov, največje odpadanje plodičev, T-stadij plodov … Fenološko to obdobje na začetku omejuje polno cvetenje, njegovo drugo polovico obeleži T-stadij, ki ga v večini let zabeležimo med 20 in 26 DAFB. Podatki o zabeleženih datumih polnega cvetenja in T-stadija za vse opazovane sorte in vsa leta našega poskusa so v preglednici 1.

Preglednica 1: Fenološki podatki za sorte in leta
Table 1: Fenological data for cv. and years

Leto in sorta	Polno cvetenje (FB)	Odstopanje od pov. FB v dnevih	T-stadij	Odstopanje od pov. T- st v dnevih	Obiranje	Št dni od FB do obiranja	Št dni od T-sadija do obiranja
06 Gala	27.4.	+7	21.5.	+6	5.9.	131	107
06 ZD	30.4.	+9	25.5.	+8	26.9.	149	133
06 Fuji	28.4.	+8	24.5.	+7	10.10.	165	139
06 Braeb	26.4.	+6	21.5.	+5	10.10.	167	142
07 Gala	16.4.	-4	7.5.	-8	16.8.	122	101
07 ZD	17.4.	-4	11.5.	-6	12.9.	148	124
07 Fuji	17.4.	-3	10.5.	-7	26.9.	162	139
07 Braeb	17.4.	-3	7.5.	-9	26.9.	162	142
08 Gala	21.4.	+1	13.5.	-2	28.8.	129	107
08 ZD	22.4.	+1	16.5.	-1	17.9.	148	124
08 Fuji	21.4.	+1	15.5.	-2	24.9.	156	132
08 Braeb	18.4.	-2	12.5.	-4	24.9.	165	135

Fenološki podatki nedvomno kažejo, da so bila leta po odzivu rastlin na vremensko dogajanje različna: leto 2006 je bilo do T-stadija izrazito kasnejše od ostalih dveh, po številu dni od FB do obiranja pa daljše od leta 2007 in zelo podobno letu 2008. Leto 2007 je ob FB in še posebej ob T-stadiju najzgodnejše leto, po številu dni od FB do obiranja pa je bilo z izjemo sorte ZD krajše od obeh ostalih let. Leto 2008 je bilo po FB in T-stadiju povprečno leto (v opazovanem triletnem obdobju), po številu dni od FB do obiranja pa zelo podobno letu 2006.

Da bi reprezentativno opisali temperaturne razmere v opazovanem obdobju, smo se zaradi primerljivosti odločili za pregled t. i. HA vsote (heat accumulation oz. akumulacija toplote). Ta je definirana kot seštevek najvišje in najnižje zabeležene dnevne temperature v nekem časovnem obdobju (Baskerville in sod., 1969).

Preglednica 2: HA temperaturne vsote po mesecih in letih za lokacijo SC Mb
Table 2: HA temperature sums for months and years at the location SC Mb

Leto	April	Maj	Junij	Julij	Avgust	Septem.	Oktober	Vsota april do oktober	% od pov.
2006	655,9	891,7	1109,9	1361,9	1078,3	1073,5	801	6972,2	100,7
2007	754,4	1020,2	1215,7	1295,5	1214,5	831,5	634	6965,8	100,6
2008	629,4	982,4	1157,7	1253,3	1224,5	875,1	714,8	6837,2	98,7
Pov.								6925,1	

Vsota HA za rastno obdobje od aprila do oktobra se med leti ne razlikuje. Pomembne razlike se pokažejo med meseci in leti: leto 2007 odstopa z visoko vsoto HA v aprilu, maju in juniju, hladnejši september in hladen oktober pa imata najverjetneje le majhen vpliv na priraščanje plodov, še posebej ne na sorti 'Gala' in 'Zlati delišes', ki sta obrani konec avgusta in v začetku septembra. Leto 2008 je v prvih treh mesecih nekoliko hladnejše od leta 2007 in nekoliko toplejše od leta 2006. Leto 2006 je najhladnejše v prvih treh opazovanih mesecih in najtoplejše v juliju, septembru in oktobru. Obdobje treh opazovanih let je najverjetneje prekratko za dokončno sklepanje o vplivu mesečne HA vsote na potek priraščanja. V našem primeru le nazorno razloži različnost temperaturnih pogojev med leti.

Glede na zapise o izrazitem vplivu temperature na zgodnji razvoj plodov (obdobje 0–40 DAFB) v literaturi (Atay in sod., 2010; Austin in sod., 1999; Blanke in Kunz, 2009; Garritz in sod., 1999; Goudrian in sod., 1990; Kaack in Pedersen, 2011; Lakso in sod., 1995; Warrington in sod., 1999; Welte, 1990; Westwood, 2009) smo za našo poskusno lokacijo in opazovana leta zbrali podatke za to obdobje po sortah in letih. Podatki so prikazani v preglednici 3.

Preglednica 3: HA za obdobje 0–40 DAFB po sortah in letih za lokacijo SC Mb
Table 3: HA for 0-40 DAFB according to cultivars and years at the location SC Mb

Leto in sorta	HA 0 – 40 DAFB	% od povp.*	Povp. temp.	% od povp.*
2006 'Gala'	1115,9	93,2	13,4	93,1
2006 'Zlati delišes'	1114,8	92,3	13,5	92,5
2006 'Fuji'	1110,3	94,3	13,4	91,2
2006 'Braeburn'	1122,8	94,6	13,5	98,6
2007 'Gala'	1259,0	105,1	15,1	104,9
2007 'Zlati delišes'	1273,0	105,4	15,3	104,8
2007 'Fuji'	1203,5	102,2	16,0	108,8
2007 'Braeburn'	1273,0	107,2	15,3	107,0
2008 'Gala'	1217,8	101,7	14,7	102,1
2008 'Zlati delišes'	1234,6	102,2	14,9	102,1
2008 'Fuji'	1217,8	103,5	14,7	100,0
2008 'Braeburn'	1165,6	98,2	14,1	98,6

*= povprečje HA ali temperature za sorto v obdobju 2006 – 2008

Tako HA vsota kot tudi povprečne dnevne temperature v času 0–40 DAFB kažejo značilnosti posameznih let: leto 2007 je najtoplejše, leto 2008 je povprečno in leto 2006 je najhladnejše. Seveda moramo upoštevati dejstvo, da so že omenjeni poskusi o vplivu zgodnjih temperatur na začetni razvoj plodov (Warrington in sod., 1999) bili izvedeni v ekstremnih razmerah. V rastnih komorah so primerjali temperaturne režime (prva številka zmeraj pomeni »dnevno temperaturo« za 12 ur in druga vedno »nočno temperaturo« za 12 ur v ^{0}C): 9/3 povprečno 6 ^{0}C; 13/3 povprečno 8 ^{0}C; 19/9 povprečno 14 ^{0}C; 25/15 povprečno 20 ^{0}C.

Če pogledamo podatke o zabeleženi velikosti in masi plodov v tabelah 3 in 4 članka (Zadravec in sod., 2013), podpoglavje 2.2., stran 20 in 21, vidimo čvrsto zvezo med sorto in velikostjo ter maso plodov: 'Zlati delišes' je v povprečju v vseh opazovanih letih najdebelejši in ima največjo maso plodov, na drugem mestu je 'Fuji', sledita pa mu enako velika in z enako maso 'Braeburn' in 'Gala'. Velike razlike med potekom fenologije in tudi precej velike razlike med temperaturnimi razmerami po mesecih niso imele nobenega vpliva. Tudi zveza med letom in povprečno velikostjo ter maso plodov je zelo čvrsta ($p = 0,003$) in pokaže, da so bili plodovi največji in so imeli največjo maso v letu 2007, med leti 2006 in 2008 pa ni statistično značilnih razlik. Tukaj se pokaže, da so razlike v obdobju FB–40 DAFB očitno vplivale na povprečno velikost in maso plodov, tako da naše meritve posredno potrjujejo v literaturi zelo pogosto navedeno zvezo med temperaturo in rastjo plodov v tej fazi. Enako drži za zvezo med sorto in letom. Plodovi sorte 'Zlati delišes' so v vseh letih najdebelejši in imajo največjo maso, v letih 2006 in 2007 se mu na prvem mestu pridruži 'Fuji', v vseh letih so plodovi teh sort večji in imajo večjo maso od plodov sort 'Braeburn' in 'Gala', ki sta v letih 2006 in 2008 enaka, v letu 2007 pa je 'Gala' najdrobnejša in ima najmanjšo maso.

V iskanju razlogov, zakaj so plodovi sorte 'Gala' v primerjavi s plodovi ostalih sort prav v, sicer povprečno »najdebelejšem«, letu 2007 statistično značilno najdrobnejši kljub za razvoj ugodnih razmerah v aprilu, maju in juniju, se zdi najverjetnejši razlog v kratkosti obdobja od FB do obiranja (122 dni–7 do 9 dni manj kot v letih 2006 in 2008). Sorta ima sicer enako priraščanje kot 'Zlati delišes' in 'Fuji', vendar občutno krajši čas takega priraščanja. Zanjo leta s hitrim zorenjem (2007) za končno velikost in maso plodov pač niso ugodna.

Plodovi sorte 'Braeburn' so v vseh letih statistično značilno drobnejši od plodov sort 'Zlati delišes' in 'Fuji'. Kljub temu, da ima sorta 'Braeburn' za rast na razpolago sicer dolgo rastno dobo – v povprečju kar 164 dni od FB do obiranja – pa je rast njenih plodov, ki ga opiše parameter $\phi 2$ statistično značilno manjša od ostalih opazovanih sort.

Naslednje vprašanje kar logično sledi iz odgovora na prvo: če znamo torej dovolj zanesljivo napovedati rast in plodov, ki poteka sortno tipično in dokaj malo odvisno od zunanjih dejavnikov, kako zanesljivo in od katere točke na krivulji rasti (od katerega dne DAFB) je zanesljivost tako velika, da postane rezultat uporaben za številne namene.

Da bi dobili odgovor na to vprašanje, smo primerjali vse meritve s končno izmerjeno velikostjo plodov ob obiranju in izračunali statistično značilnost korelacije ter netočnost napovedi. Pokazala se je različnost med zgodaj zorečima sortama 'Gala' in 'Zlati delišes' in kasno zorečima 'Braeburn' in 'Fuji'. Obe pozno zoreči sorti sta bolj zgodaj v rastni dobi dosegla visok koeficient determinacije. Čeprav ni jasno postavljenih meril, pri kakšni višini koeficienta determinacije lahko govorimo o zadostnem deležu pojasnjene variabilnosti v tako zapletenem procesu kot je priraščanja plodov, smo si postavili to mejo pri 75 %. Sorta 'Braeburn' je to mejo dosegla 84 DAFB, 'Fuji' okoli 115 DAFB, 'Gala' okoli 104 DAFB in 'Zlati delišes' pri 115 DAFB. Naše pričakovanje, da bomo dovolj točni z napovedjo že 100 DAFB, se je potrdilo le pri sorti 'Braeburn', pri ostalih pa je cilj dosežen nekaj dni kasneje. V zgodnjem letu (2007) lahko končno velikost plodov pri sorti 'Braeburn' napovemo že okoli 10. julija, za ostale sorte pa zadnje dni julija ali prve dni avgusta. V poznih letih (2006) je to še okoli 10 dni kasneje. Za podporo tehnološkim odločitvam, ki bi še lahko vplivale na končno velikost plodov (dodatno ročno redčenje), je v tem času že prepozno (Tromp in sod., 2005). Za načrtovanje organizacije obiranja (količina potrebne delovne sile, količina potrebne embalaže) in za trženjske aktivnosti (napoved pridelka po sistemu »Prognosfruit« – prva dekada avgusta, najava količin in pričakovanih velikosti plodov kupcem) pa še pravočasno.

O vplivu gostote oveska plodov (število plodov na drevo, število plodov cm^2 preseka debla – TCSA) na velikost plodov, na zunanjo in notranjo kakovost plodov ter na cvetenje v naslednjem letu (returned bloom), je veliko znanega (Beber, 2009). Ali različne obremenjenosti dreves povzročijo tudi različen potek priraščanja plodov, pa je mnogo manj raziskano področje. Še posebej malo je znanega o vplivu gostote oveska plodov na točnost napovedovalnih modelov. V drugem poskusu, ki smo ga na isti lokaciji v letih 2009, 2010 in 2011 izvedli na sorti 'Gala', nas je zanimalo prav to.

Sorta 'Gala' spada med tiste, ki so v masi pridelka v večletnem obdobju dokaj stabilne, saj ni nagnjena k pojavu alternativne rodnosti. Prav zaradi tega smo med seboj primerjali potek priraščanja plodov na drevesih z gostoto oveska, ki je primerljiva z običajnim v rodnih nasadih (50–100 plodov na drevo ali 10–18 kg/drevo ali 30–55 t/ha).

V našem poskusu v poprečju 3 let med obravnavanji nismo zabeležili razlik v velikosti in masi plodov ob obiranju pri različnih obremenitvah dreves (4 pl/cm^2 TCSA – 81,95 mm in 203,11 g; 7 pl/cm^2 TCSA – 81,52 mm in 202,55 g; 9 pl/cm^2 TCSA – 82,33 mm in 208,87 g). To je v nasprotju z ugotovitvami drugih avtorjev, ki so recimo za sorto 'Fuji' dokazali vpliv gostote oveska na končno maso plodov (Jakopič in sod., 2013). Velik povprečni premer in veliko povprečno maso plodov v vseh obravnavanjih pripisujemo dejstvu, da je bil izbran razpon obremenitev dokaj majhen in tako najmanjša kot tudi največja izbrana obremenitev nista bili ekstremni. Če primerjamo med seboj leta v opazovanem obdobju, pa ugotovimo, da smo sicer zabeležili največjo velikost in maso plodov v letu 2009 (83,97 mm in 221,33 g), na drugem mestu je leto 2011 (81,99 mm in 205,89 g) in na tretjem mestu leto 2010 (79,87 mm in 190,66 g).

Preglednica 4: Fenološki podatki za sorto 'Gala' na lokaciji SC Mb po letih
Table 4: Fenological data for cv. ' Gala' at the location SC Mb in years

Leto	Polno cvet. FB	Odstopanje od pov. FB v dnevih	T-stadij	Odstopanje T-st.od pov. v dnevih	Obiranje	Št dni od FB do obiranja	Št dni od T-sadija do obir.
2009	18.4.	-3	11.5.	-3	18.8.	122	99
2010	27.4.	+6	16.5.	+2	02.9.	128	109
2011	17.4.	-4	15.5.	+1	26.8.	131	103

Fenološki podatki nedvomno kažejo, da so bila leta po odzivu rastlin na vremensko dogajanje različna: leti 2009 in 2011 sodita po datumu polnega cvetenja med zgodnejši leti in sta občutno zgodnejši od leta 2010. Leta 2009 so plodovi dosegli T-stadij že 11. 5., po 23 dneh. Leta 2010 so plodovi dosegli T-stadij nekaj dni kasneje (16. 5.), a po krajšem obdobju, po 19 dneh. V letu 2011 je bil T-stadij dosežen le dan prej (15. 5.), a po najdaljšem obdobju od polnega cvetenja do T-stadija, po 28 dneh. Tudi po datumu obiranja so leta med seboj dokaj različna: leta 2009 smo obirali zelo zgodaj: 18. 8., kar je 122 dni od polnega cvetenja in 99 dni od T-stadija. Leto 2010 je bilo tudi po obiranju najkasnejše leto, a je zaradi kasnega cvetenja preteklo do obiranja 128 dni, od T-stadija 109 dni. Leta 2011 je bilo obiranje izvedeno 26. 8., kar je tudi zelo blizu dolgoletnega povprečja obiranja za sorto 'Gala' na lokaciji SCMb. To pomeni, da smo obirali 131 dni po polnem cvetenju in 103 dneve po T-stadiju.

Preglednica 5: HA temperaturne vsote po mesecih in letih ter odstopanje od tri letnega povprečja v % za lokacijo SC Mb
Table 5: HA temperature sums for months and years and the deviation from the three-year average in % at the location SC Mb

Leto	april	maj	junij	julij	avgust	∑ HA april do avgust	% od HA pov.
2009	841,6	1039,8	1061,9	1296,8	1307,2	5547,3	102,6
2010	648,2	941,0	1151,5	1383,5	1213,0	5337,2	98,7
2011	796,4	918,1	1125,5	1198,4	1295,6	5334,0	98,7
HA povp.						5406,2	

Leto 2009 je po HA vsoti za obdobje april–avgust sicer najtoplejše, a od obeh drugih let odstopa le za 3,9 %. Najočitnejša je razlika v aprilu in maju, ko ima temperatura po trditvah številnih avtorjev tudi največji vpliv na končno debelino plodov (Tromp in sod., 2005). Za še natančnejši vpogled v vremensko (temperaturno) dogajanje v času od polnega cvetenja do 40 dni po polnem cvetenju (HA 0–40 DAFB) smo pripravili preglednico 6, v kateri so prikazane razlike v HA vsoti po letih.

Preglednica 6: HA za obdobje 0 – 40 DAFB za sorto 'Gala' po letih na lokaciji SC Mb
Table 6: HA for 0-40 DAFB for cv. 'Gala' in years at the location SC Mb

Leto	HA 0 – 40 DAFB	V % od povp. treh let
2009	1329,1	106
2010	1250,2	99,7
2011	1181,0	94,2

Leto 2009 je bilo tudi v obdobju 0–40 DAFB po kriteriju HA najtoplejše, sledi mu leto 2010, najhladnejše je leto 2011.

V letu 2009 smo torej z modelnim izračunom napovedali in tudi dejansko izmerili in stehtali največje in najtežje plodove, navkljub dejstvu, da je bil čas od polnega cvetenja do zorenja in tudi čas od T-stadija do zorenja v primerjavi z ostalima letoma najkrajši. To pomeni, da so plodovi v tem letu priraščali hitreje kot v drugih dveh in s precejšnjo gotovostjo lahko tudi na podlagi naših meritev posredno sklepamo, da je za potek priraščanja v obdobju od polnega cvetenja do zorenja najpomembnejša toplota v obdobju 0–40 DAFB.

Da bomo lažje analizirali vpliv oveska na parametre modela, smo pripravili preglednico 7, v kateri smo prikazali povprečne parametre rasti za modificirano Gompertzovo funkcijo po naših meritvah. Modificirano Gompertzovo funkcijo smo uporabili zaradi dejstva, da jo uporabljajo za namen napovedovanja pridelka jabolk tudi v ostalih evropskih državah, ki sodelujejo v projektu 'Prognosfruit'.

Preglednica 7: Povprečni parametri rasti za modificirano Gompertzovo funkcijo pri sorti 'Gala' ob različnih gostotah oveska plodov na lokaciji SCMb v obdobju 2009–2011

Table 7: Average growth parameters for modified Gompertz function for cv. 'Gala' at different crop load density on the location SCMb from 2009 to 2011

Ovesek	α	ϒ	β
4 pl/ cm^2 TCSA	83,16	2,043	0,0479
7 pl/ cm^2 TCSA	82,6	2,191	0,0643
9 pl/ cm^2 TCSA	81,53	2,169	0,0720

Parameter α (opiše največjo možno končno velikost plodu) je pričakovano največji ob najmanjšem ovesku in najmanjši ob največjem ovesku. Razlike med obravnavanji so zelo majhne, glede na simulacijo vpliva tega parametra na potek priraščanja lahko utemeljeno pričakujemo, da ima le minimalni vpliv na potek priraščanja (Welte, 1994).

Parameter ϒ (določa zakasnitev rasti po cvetenju) je najmanjši pri najmanjšem ovesku in največji pri največjem ovesku. Ker po simulaciji manjša vrednost tega parametra pomeni zgodnejše in nekoliko večje priraščanje, je tudi to logično pričakovano.

Kot kažejo naši podatki, je od gostote oveska najbolj odvisen parameter β (določa, kako močno bo rast upadla, ko plod doseže največje povečanje svoje mase). Po simulacijah je njegov vpliv na potek priraščanja in končno velikost in maso plodov relativno močan. Čim večji je parameter, tem večja sta, ob enaki dolžini obdobja od FB do obiranja, končna velikost in masa plodov. Njegov vpliv je povezan z dolžino rastne dobe plodov (eksponent β*t).

Ker smo tako po dejansko tehtani kot tudi po modelno napovedani končni masi plodov med obravnavanji zabeležili le sorazmerno majhne razlike in sta parametra α in ϒ le malo različna, lahko upravičeno domnevamo, da prav parameter β v našem primeru res najmočneje vpliva na končno maso plodov in s povečanjem oveska plodov narašča.

Namen naše raziskave je bil na koncu tudi preveriti, ali lahko s prilagajanjem parametrov v Gompertzovi funkciji izboljšamo natančnost napovedovanja končnega pridelka v nasadih sorte 'Gala'.

Najprej smo preverili natančnost povprečnega večletnega modela, ki za vrednosti parametrov vzame: α = 80,676; ϒ = 2,1218 in β = 0,0384. Izračunane modelne vrednosti za skupni pridelek smo primerjali z dejansko obrano maso pridelka in ugotovili, da smo z modelnim izračunom statistično značilno zgrešili v letih 2009 (modelno podcenjen pridelek za 1.042 kg/ha ali –5,1 %) in v letu 2010 (modelno precenjen pridelek za 7.441 kg/ha ali +27,3 %). Povprečni večletni model je statistično značilno natančno napovedal pridelek v letu 2011 (modelna napoved podceni pridelek za 444 kg/ha ali za –1,5 %). Ugotovimo torej lahko, da smo že s povprečnim večletnim modelom cilj praktično dosegli v letih 2009 in 2011. Močno smo ga z zgrešili v letu 2010. Za lažjo primerjavo parametrov dolgoletnega povprečnega modela in korigiranih parametrov na podlagi naših triletnih meritev smo pripravili preglednico 8, v kateri prikazujemo vrednosti modelnih parametrov za opazovana leta v primerjavi z večletnim povprečjem teh parametrov.

Preglednica 8: Vrednosti parametrov za standardno in modificirano Gompertzovo funkcijo pri sorti 'Gala' na lokaciji SC Mb v letih 2009–2011 v primerjavi z večletnim povprečjem

Table 8: Parameter values for standard and modified Gompertz function with cv. 'Gala' at the location SC Mb from 2009 to 2011 in comperison with long term everage

Leto	α	ϒ	β
Dolgoletno povp.	80,676	2,1218	0,0384
2009	82,47	2,140	0,083
2010	80,03	1,935	0,061
2011	84,72	2,328	0,041

Razloge za močno odstopanje dolgoročne modelne napovedi v letu 2010 v primerjavi z dejansko obranimi pridelki v 28 slovenskih nasadih sorte 'Gala' je potrebno iskati v značilnostih letnika. Po hladnem aprilu (HA april 2010 = 648,2; 2009 = 841,6; 2011 = 796,4) je termin polnega cvetenja FB v tem letu 27. april. Temperaturne razmere v letu 2010 od FB do 40 DAFB so sicer nekoliko slabše kot v letu 2009, a boljše kot v letu 2011 (HA 0–40 DAFB: 2009 = 1329,1; 2010 = 1250,2; 2011 = 1181,0). To in morda tudi zelo kasno cvetenje je omogočilo doseganje T-stadija v letu 2010 že po 19 dneh (hitreje kot v letu 2009: 23 dni in letu 2011: 28 dni). Začetni razvoj plodov v modelu opredeli parameter ϒ in naši izračuni za leto 2010 kažejo, da je ta manjši ter očitno odstopa od dolgoletnega.

Od dolgoletnega parametra β v povprečnem dolgoletnem modelu odstopa tudi naš izmerjeni korigirani parameter β za leto 2010. Napovedana končna povprečna masa plodu (povprečje vseh obremenitev in vseh pozicij plodov) bi po korekciji parametrov le za 3,71 % presegala dejansko stehtano, kar pomeni, da bi s korekcijo parametrov lahko občutno izboljšali točnost napovedi in tudi v tem letu dosegli postavljeni cilj. Trenutna težava je v tem, da zaenkrat ne znamo določiti korigiranih parametrov dovolj zgodaj v rastni sezoni.

3.2.SKLEPI

Z meritvami priraščanja plodov v več letih in na več sortah smo želeli dognati, kako čvrsto je potek priraščanja plodov povezan s sorto – koliko je gensko opredeljen in koliko je morda odvisen od dejavnikov okolja. Zanimalo nas je, ali krivulja priraščanja v različnih letih poteka enako in kdaj v razvojnem poteku plodov bi lahko s primerno zanesljivostjo napovedali končno velikost plodov. Z ločenim poskusom smo želeli tudi ugotoviti, koliko na potek priraščanja plodov vplivamo z redčenjem plodov in ali različne gostote oveska plodov pomenijo tudi različno dinamiko in končno velikost plodov pri sorti 'Gala'. Za to sorto smo z uporabo v poskusu korigiranih modelnih parametrov tudi preverili izboljšanje natančnosti napovedi pogosto uporabljenega napovedovalnega modela.

Rezultati naših meritev in njihova interpretacija je podala odgovore na vse postavljene raziskovalne hipoteze.

Najpomembnejši sklepi našega raziskovalnega dela, ki izvirajo iz prvega poskusa, so:

- Izrisane krivulje priraščanja plodov pri vseh sortah in v vseh opazovanih letih kažejo tipično negativno eksponentno obliko ter so med sortami in leti dokaj podobne. Od ocenjevanih dejavnikov je dejavnik položaja plodu (na enoletnem poganjku terminalno, na brstiču dvoletnega lesa, na brstiču ali brstiki 3-letnega lesa) brez vpliva na priraščanje plodov.
- V von Bertalanffyjevi enačbi uporabljeni trije faktorji, izračunani za naše meritve, in za vse v naš poskus vključene sorte, so:

  ϕ 1: 93,5 (92,2–94,8)

  ϕ 2: –4,43 (–4,46 do –4,41)

  ϕ 3: 9,2 (8,75–9,65)

  Koeficient determinacije r^2 povprečnega modela je 91,3 %. Parameter ϕ 1 (potencialna končna velikost plodu) je statistično značilno odvisen od sorte, ni odvisen od leta, zanj je potrjena šibka interakcija med sorto in letom. To nakazuje, da je z modelom napovedana končna velikost plodu (opisana kot asimptota krivulje) genetsko nadzorovana (vodena) in nanjo le zmerno vplivajo drugi notranji (položaj plodu) in zunanji (vpliv leta oziroma vreme) analizirani dejavniki.

- Razlika med napovedano končno velikostjo plodu in dejansko izmerjeno končno velikostjo plodu je največja pri sorti 'Gala', delež pojasnjene variance je najmanjši (r^2 = 0,37). Nekoliko bolje je pri sortah 'Braeburn' (r^2 = 0,49) in 'Zlati delišes' (r^2 = 0,67). Najbolje je pri pozno zoreči sorti 'Fuji' (r^2 = 0,75). Dokaj verjetno je predvidevanje, da zgodnje sorte dosežejo tehnološko zrelost relativno zgodaj v svojem razvojnem obdobju in bi se rast plodov teoretično še nadaljevala tudi po doseženi tehnološki zrelosti.
- Parameter ϕ 2, ki določa naklon krivulje, pokaže stopnjo priraščanja sorte. Statistično značilno so potrjene razlike med sortami in leti, ni pa bilo interakcije med njimi. Sorte 'Gala', 'Zlati delišes' in 'Fuji' imajo podobne stopnje priraščanja, med njimi ni statistično značilnih razlik. Počasnejše priraščanje pa je značilno za sorto 'Braeburn'.
- Na podlagi naših rezultatov lahko sklepamo, da je negativna eksponentna oblika priraščanja univerzalna za sorte jabolk v enakih okoliščinah za čas od T-stadija do tehnološke zrelosti, torej linearno povečevanje premera plodov, ki mu sledi upočasnjeno priraščanje v zadnji fazi rasti. Zgodaj zoreča sorta 'Gala' kaže relativno linearno priraščanje debeline plodov skoraj do dosežene tehnološke zrelosti in obiranja.

- Ugotovili smo čvrsto zvezo med sorto in velikostjo ter maso plodov: sorta 'Zlati delišes' v povprečju v vseh opazovanih letih doseže največji premer in največjo maso plodov, na drugem mestu je sorta 'Fuji', sledita enako velika in z enako maso sorti 'Braeburn' in 'Gala'. Velike razlike med potekom fenologije in tudi precejšnje temperaturne razlike po mesecih niso imele nobenega vpliva na razvrstitev sort po velikosti in masi. Tudi zveza med letom in povprečno velikostjo ter maso plodov je zelo čvrsta (p = 0,003) in pokaže, da so bili plodovi največji in najtežji v letu 2007, v letih 2006 in 2008 pa med seboj enaki. Pokazalo se je tudi, da so razlike v obdobju FB–40 DAFB očitno vplivale na povprečno velikost in maso plodov.
- V zgodnjem letu (2007) lahko končno velikost plodov pri sorti 'Braeburn' napovemo že okoli 10. julija, za ostale sorte pa zadnje dni julija ali prve dni avgusta. V poznih letih (2006) je to okoli 10 dni kasneje. Za podporo tehnološkim odločitvam, ki bi še lahko vplivale na končno velikost plodov (dodatno ročno redčenje), je v tem času že prepozno, medtem ko je za načrtovanje organizacije obiranja (količina potrebne delovne sile, količina potrebne embalaže in količina potrebnega skladiščnega prostora) in za trženjske aktivnosti (napoved pridelka po sistemu »Prognosfruit« – prva dekada avgusta, najava količin in pričakovanih velikosti plodov kupcem) še pravočasno.

V drugem poskusu, v katerem smo na sorti 'Gala' preverjali vpliv gostote oveska plodov na potek priraščanja plodov in tudi natančnost napovedovalnega modela, smo ugotovili:

- V našem poskusu v povprečju 3 let med obravnavanji nismo zabeležili razlik v velikosti in masi plodov ob obiranju. Velik povprečni premer in maso plodov v vseh obravnavanjih pripisujemo dejstvu, da je bil izbrani razpon obremenitev dokaj majhen in tako najmanjša kot tudi največja izbrana obremenitev nista bili ekstremni.
- Dolžina rastne dobe od FB do obiranja pri sorti 'Gala' ne vpliva na končno velikost plodov.
- Na končno velikost plodov imajo najbrž največji vpliv temperature v času cvetenja in kmalu po njem (0–40 DAFB).
- Od modelnih parametrov (α, β in ϒ) v uporabljeni Gompertzovi funkciji je po naših meritvah od oveska in leta najbolj odvisen parameter β.
- Povprečni napovedovalni model po Welteju in Stanleyju je v dveh od treh opazovanih let primerno natančno napovedal skupno končno maso pridelka (95% točnost).
- Za izboljšanje natančnosti napovedi s korekturo modelnih parametrov bo z nadaljnjimi raziskavami potrebno razviti metodo za njihovo korekcijo že zgodaj v sezoni, najbrž nekje med 50 in 100 dnevi po polnem cvetenju.

Rezultati našega raziskovalnega dela so pomemben prispevek razvoju znanosti pri prizadevanjih za čim natančnejše napovedovanje pridelka jabolk. Ugotovili smo, da pomembni sorti novejšega svetovnega sortimenta, 'Gala' in 'Fuji', priraščata po enakem vzorcu kot že do sedaj dobro raziskana sorta 'Zlati delišes'. Naša ugotovitev, da položaj plodu v krošnji gojitvene oblike ozkega vretena ne vpliva na značilnosti in potek priraščanja plodov, bo prav tako olajšala potek vzorčenja za določanje števila plodov na drevesu. Tudi ugotovitev, da zunanji dejavniki le malo vplivajo na končno velikost plodov, je pomembna in daje modeliranju priraščanja večjo težo. Potrdili smo, da je izboljšanje natančnosti zelo razširjenega napovedovalnega modela na podlagi Gompertzove funkcije mogoče predvsem z nadaljevanjem raziskav za zgodnje določanje parametra β, ki se najmočneje odziva na gostoto oveska plodov.

4 POVZETEK (SUMMARY)

4.1 POVZETEK

V dveh večletnih poskusih, izvedenih na lokaciji Sadjarski center Maribor (46^{o}61'N, 15^{o}69'E; 280m NM), smo na več sortah žlahtne jablane spremljali priraščanje plodov (povečevanje ekvatorialnega premera plodov) v času od T-stadija do zorenja. V prvem poskusu na sortah 'Gala' Brookfield®, 'Zlati delišes' Reinders®, 'Fuji' Kiku® in 'Braeburn' Hillwell® smo v letih 2006, 2007 in 2008 z meritvami v tedenskih presledkih dokazali, da priraščanje plodov poteka v obliki negativne eksponentne enačbe. Za primeren nelinearni model priraščanja smo izbrali von Bertalanffyjevo enačbo in zanjo določili sledeče povprečne parametre za vse obravnavane sorte: ϕ1: 93,5 (92,2–94,8), ϕ2: –4,43 (–4,46–4,41) in ϕ3: 9,2 (8,75–9,65). Koeficient determinacije za povprečni model je 91,3 %. Vse sorte, vključene v spremljanje, kažejo podobne značilnosti priraščanja z linearnim naraščanjem premera v začetku rasti (od 40 DAFB pa do nekaj tednov pred obiranjem). Naklon krivulje v tem obdobju popiše parameter ϕ2, ki se ne razlikuje pri sortah 'Gala', 'Zlati delišes' in 'Fuji' in je statistično značilno nižji pri sorti 'Braeburn' – ta prirašča počasneje. Priraščanje v tem obdobju je odvisno od sorte in leta. Temu sledi upočasnjeno priraščanje do asimptote, dosežene ob tehnološki zrelosti (obiranju). Končna velikost plodov (asimptota) je bila značilno odvisna od sorte. Najdebelejše plodove smo izmerili pri sorti 'Zlati delišes' (78,3 mm), ki ji sledi 'Fuji' (75,7 mm), temu pa 'Gala' (72,0 mm) in 'Braeburn' (70,6 mm). Višjo korelacijo med napovedano in izmerjeno končno velikostjo plodov smo zabeležili pri pozno zorečih sortah. Primerjali smo tudi razvoj plodov glede na njihov položaj na rodnem lesu: terminalno na enoletnem poganjku, terminalno na brstiki na dvoletnem lesu ter terminalno na brstiču na triletnem lesu. Ugotovili smo, da položaj plodu ne vpliva na njegovo priraščanje. Z analizo podatkov o priraščanju smo določili tudi povprečni termin v tem procesu, izražen kot dan po polnem cvetenju (DAFB), ko lahko z dovolj veliko zanesljivostjo napovemo končno velikost plodov pri vsaki od opazovanih sort. Pričakovanja, da to lahko določimo že 100 dni po polnem cvetenju, nismo povsem dosegli, smo se mu pa zelo približali. Ugotovili smo, da lahko z natančnostjo r^2 nad 0,75 določimo končno velikost plodu za vse opazovane sorte okoli 110 DAFB. Natančnost je po naših meritvah boljša pri kasno zorečih sortah.

V drugem poskusu smo v letih 2009, 2010 in 2011 na sorti 'Gala' Schniga® preverjali vpliv gostote oveska plodov, izraženega v številu plodov na cm^2 preseka debla (TCSA) (nizka obremenitev 4 pl/cm^2 TCSA, srednja obremenitev 7 pl/cm^2 TCSA in visoka obremenitev 9 pl/cm^2 TCSA), na priraščanje in točnost napovedi končne mase pridelka. Ugotovili smo, da gostota oveska v razponu med 4 in 9 pl/cm^2 TCSA ne vpliva na končno velikost plodov. Prav tako naše meritve kažejo, da različna dolžina rastne dobe plodov (med 122 in 131 od FB do obiranja) ne vpliva na končno velikost plodov. Na osnovi analize meteoroloških podatkov domnevamo, da ima na končno velikost plodov največji vpliv toplota v začetni fazi razvoja plodov. Povprečni parametri napovedovalnega modela po Gopertzovi funkciji

v večini let z zadovoljivo natančnostjo (95%) napovedo končno maso pridelka pri sorti 'Gala'. Na podlagi naših meritev korigirani parametri sicer izboljšajo natančnost napovedi, vendar je za zdaj težava v tem, da jih lahko določimo »za nazaj«. Nadaljnje raziskave povezanosti parametrov funkcije z najpomembnejšimi spremenljivkami v okolju (najbrž s temperaturo) bi lahko omogočile še večjo natančnost napovedi in jo bolj povezale z letom za katerega napovedujemo pridelek.

4.2 SUMMARY

In several two-year experiments performed at Sadjarski center Maribor (46^{o}61'N, 15^{o}69'E; 280m NM) we monitored the fruit growth rate (enlargening the equatorial diameter of fruit) at more variety of domesticated apple from T-stadium till ripening. At the first experiment on 'Gala' Brookfield®, 'Golden Delicious', Reinders® 'Fuji', Kiku® and 'Braeburn' Hillwell® in 2006, 2007 and 2008, by measurings performed in weekly intervals, we have proven that the fruit growing rate runs in a form of a negative exponential equation. For a suitable non-linear model of fruit growing we used von Bertalanffy equation for which we determined the following average parameters for all the selected varieties: ϕ1: 93,5 (92,2 - 94,8), ϕ2: –4,43 (–4,46 - –4,41) in ϕ3: 9,2 (8,75 - 9,65). The coefficient of determination for an average model is 91,3%. The mean squared error is 0,997. All included varieties show similar fruit growth rate characteristics, with linear growth of the diameter in the early stage of growth (from 40 DAFB to a few weeks before harvest). The inclination of the curve at this stage is described by the parameter ϕ2, which is no different with 'Gala', 'Golden Delicious' and 'Fuji', and is statistically lower with 'Braeburn' which has a slower growing rate. The fruit growing rate is dependent on the variety and the year. The early stage of growth is followed by the slow growth to the asymptote reached at the technological ripeness (harvest).

The final size of fruit (asymptote) was typically dependent on the variety. The thickest fruit was measured at 'Golden Delicious' (78,3 mm), which was followed by 'Fuji' (75,7 mm), 'Gala' (72,0 mm) and 'Braeburn' (70,6 mm). Higher correlation between predicted and measured final size of the fruit was noted with late-ripening varieties. We also compared the development of the fruit according to their position on fruiting wood: terminal on 1-year shoots, on 2-years and on 3-years shoots.

We found out that the position of the fruit does not influence its fruit growth rate. By analysing the fruit growing data we determined the average date in this process, which is expressed as the day after the full bloom (DAFB), when we can forecast the final size of the fruit with sufficient reliability for each monitored variety. The expectations that we would be able to forecast the size 100 days after full bloom were not fully met but we were very close. We discovered that we can, with accuracy r^2 above 0,75, determine it for all the monitored varieties around 110 DAFB. The accuracy is better with late-ripening varieties.

During the second experiment with variety 'Gala' Schniga® in 2009, 2010 and 2011 we considered the impact of crop load density expressed in number of fruit per cm^2 trunk cross-sectional area (TCSA) (low-loaded trees with 4 fruits/cm^2 TCSA, middle-loaded trees with 7 fruits/cm^2 TCSA, and high-loaded trees with 9 fruits/cm^2 TCSA), fruit growth rate and accuracy of the predicted final mass of crop. We discovered that the crop load density between 4 and 9 fruits/cm^2TCSA does not influence the final fruit size. At the same time our measurements show that different fruit growing periods (from 122 to 131 FB to harvest) do not influence the final fruit size. According to the analysis of meteorological data we assumed that the final size of the fruit was mostly influenced by the temperature in the fruit's early stage of growth. The average parameters of forecast based on Gompertz function predict final mass of crop of variety 'Gala' with satisfactory accuracy (95%) in most years.

Based on our measurements, the corrected parameters improve the accuracy of the predictions, but they can only be determined at the end of the growing period. The future research on how parameters are linked to the most important environmental variables (probably the temperature), could contribute to higher accuracy of the forecast and connect it to the specific growing season for which we predict the crop.

5 VIRI

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Vsem, ki ste me vzgajali, me učili, mi pomagali, ali pa me le prijazno spremljali skozi življenje – prisrčna hvala!

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