ALEKSANDRAS STULGINSKIS UNIVERSITY

LITHUANIAN RESEARCH CENTRE FOR AGRICULTURE AND FORESTRY

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THE EFFECTS OF ORGANIC AND MINERAL FERTILISERS ON MAIZE N STATUS UNDER WATER AND COLD STRESS CONDITIONS IN A NEMORAL CLIMATE

DOCTORAL DISSERTATION

Agricultural Sciences
Agronomy (01A)

Akademija, 2018

This research was carried out at the Lithuanian Research Centre for Agriculture and Forestry from 2014–2018.

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The doctoral dissertation will be defended at the Council of Defence of Agricultural Sciences (Agronomy):

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The defence of the doctoral thesis will be held at the public meeting of the Council of Defence for Agronomy Science on the 14th of December, 2018 at 1 p.m. in room No. 217, Central Building of the Aleksandras Stulginskis University.

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English Language Editor:
Proof-Reading-service.com, UK

Lithuanian Language Editor
Daiva Puidokienė
Lithuanian Research Centre for Agriculture and Forestry

ISBN 978-609-449-140-5

This doctoral thesis is available at the libraries of the Lithuanian Research Centre for Agriculture and Forestry and the Aleksandras Stulginskis University.

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ABBREVIATIONS

AE_N – agronomic N efficiency coefficient
CC – canopy cover
ET_0 – reference Penman-Monteith evapotranspiration
EU – European Union
FAO – Food and Agriculture Organization
FC – soil water content at field capacity
GDD – sum of growing degree days
GY – grain yield
HI – harvest index
K – potassium
KHI – potassium harvest index
K_{sat} – saturated hydraulic conductivity
LAI – leaf area index
N – nitrogen
NHI – nitrogen harvest index
N_{min} – soil mineral N content ($N\text{-}NO_3 + N\text{-}NH_4$)
NNI – nitrogen nutrition index
N_{total} – total nitrogen content
NUE – nitrogen use efficiency
P – phosphorus
PE_N – physiological efficiency
PFP_N – partial factor productivity
PHI – phosphorus harvest index
PWP – permanent wilting point
R – maize reproductive development stage
RE_N – crop recovery efficiency
RMSE – root mean square error
SAT – soil water content at saturation
SWC – soil volumetric water content
TAB − total above-ground biomass
TAW – total available water content
V – maize vegetative development stage

PADĖKA

Pirmiausiai, norėčiau padėkoti savo mokslinio darbo vadovui dr. Sigitui Lazauskui už nuolatinį palaikymą doktorantūros studijų metu, už kantrybę, patarimus, idėjas bei pasiūlymus. Studijų metu mes turėjome daugybę susitikimų, kurių metu diskutavome įvairiais klausimais, tai man padėjo tobulėti ne tik kaip mokslininkui, bet ir kaip žmogui, už tai visados būsiu dėkingas. Dėkoju Augalų mitybos ir agroekologijos skyriaus techniniams darbuotojams už pagalbą atliekant eksperimentinius tyrimus. Dėkoju dr. Jonui Volungevičiui už išsamų tyrimų vietos dirvožemio aprašymą. Nuoširdžiai dėkoju Vokietijos aplinkosaugos fondui, kuris finansavo mano stažuotes (2017 03 01 – 2017 08 06), Jülich tyrimų centre, agrosferos institute, Vokietijoje. Dėkoju agrosferos instituto direktoriui prof. dr. Harry Vereecken už tai, kad suteikė galimybę atlikti nuostabią praktiką. Ypatingai dėkoju savo tiesioginiams vadovams stažuotės metu, dr. Lutz Weihermüller ir dr. Michael Herbst, kurie yra neabejotini profesionalai savo srityje, ir kiekviena diskusija su jais suteikė man papildomų mokslinių žinių. Dėkoju savo draugams Vokietijoje, Anne Klosterhalfen už pagalbą įvairiais klausimais, Hongjuan Zhang už įdomias diskusijas apie mokslą ir kitas temas, Jūs visada man būsite pavyzdys, kaip nuosekliai dirbti ir siekti savo tikslų. Dėkoju Kamilei už visokeriopą paramą. Galiausiai norėčiau išreikšti didelę padėką savo tėvams, už besąlygišką paramą, meilę bei nuolatinį palaikymą.

ALEKSANDRO STULGINSKIO UNIVERSITETAS

LIETUVOS AGRARINIŲ IR MIŠKŲ MOKSLŲ CENTRAS

Renaldas Žydelis

ORGANINIŲ IR MINERALINIŲ TRĄŠŲ POVEIKIS KUKURŪZŲ MITYBAI AZOTU VANDENS IR ŽEMOS TEMPERATŪROS STRESŲ SĄLYGOMIS NEMORALINĖJE KLIMATO ZONOJE

DAKTARO DISERTACIJOS SANTRAUKA

Žemės ūkio mokslai
Agronomija (01A)

Akademija, 2018

Daktaro disertacija rengta 2014–2018 metais Lietuvos agrarinių ir miškų mokslų centro filiale Žemdirbystės institute.

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Disertacija bus ginama viešame Agronomijos mokslo krypties tarybos posėdyje 2018 m. gruodžio 14 d., 13 val. Aleksandro Stulginskio universiteto centrinių rūmų posėdžių salėje 217 kab.

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Disertaciją ir jos santrauką galima peržiūrėti Lietuvos agrarinių ir miškų mokslų centro filialo Žemdirbystės instituto bei Aleksandro Stulginskio universiteto bibliotekose.

ĮVADAS

Temos aktualumas

Kukurūzai (*Zea mays* L.) yra vieni iš trijų pagrindinių augalų pasaulyje, svarbiausių maisto, pašarų ir kuro šaltinių (Tenaillon ir Charcosset, 2011). Europos Sąjungoje kukurūzų grūdų derlius sudaro 20,8 % viso javų derliaus (FAOSTAT, 2016), be to, yra prognozuojama, kad iki 2026 m. kukurūzų pasėlių plotai ir toliau didės (~8 %). Tikėtina, jog kukurūzų plotai ateityje plėsis dėl didesnio nei kitų javų derlingumo potencialo, ypač pastaraisiais metais į Europos Sąjungą priimtose šalyse, kuriose derlingumo potencialo atotrūkis nuo faktinio derlingumo ūkininkų laukuose yra didžiausias (EU Commission, 2016).

Lietuvoje kukurūzai grūdams auginami nuo 2002 m. (plotas – 2,900 ha^{-1}), o per pastaruosius penkerius metus jų auginimo plotai gerokai padidėjo – nuo 9,930 iki 19 000 ha^{-1} (FAOSTAT, 2017).

Pasaulyje kukurūzų grūdų produkcija esmingai pradėjo didėti nuo 1930 m., kai buvo sukurtos naujos hibridinės kukurūzų veislės ir pradėtos taikyti naujos auginimo technologijos (Tollenaar ir Lee, 2011). Vis dėlto šiaurinėse platumose ilgą laiką rimta problema buvo trumpas auginimo sezonas ir žema oro temperatūra, tačiau trumpos vegetacijos veislės pagerino augalų adaptaciją prie nepalankių klimato sąlygų (Riva-Roveda ir kt., 2016).

Šiaurės Europoje ir Baltijos šalyse kukurūzai dažniausiai yra auginami pašarams, ir tik nedideli plotai Danijoje, Švedijoje bei Lietuvoje pasėjami grūdams (Swensson, 2014). Šiaurės Europoje kukurūzų auginimo plotai sparčiai didėja, tačiau trumpas auginimo sezonas, ankstyvos ir vėlyvos šalnos, kritulių kiekis, kuris kukurūzų auginimo laikotarpiu paprastai nesutampa su augalų vandens poreikiu, ir vis dažniau pasitaikantys sausringi periodai yra laikomi pagrindiniais veiksniais, kurie šiame regione vis dar riboja šių augalų plėtrą (Olesen ir kt., 2011).

Lauko eksperimentuose atskirti temperatūros ir vandens streso poveikį augalo vystymuisi sudėtinga ir brangu, todėl vis dažniau naudojami augalų modeliai, kurie pritaikomi daugeliui augalų, taip pat ir kukurūzams. Remiantis išsamiais eksperimentiniais duomenimis modeliai gali būti kalibruojami ir patikrinami, o tai leidžia geriau suprasti augalų augimą, vystymąsi ir derliaus mažėjimą dėl temperatūros ir vandens streso poveikio. Nors kukurūzų auginimo plotai vis dar plečiasi, o augalų modeliai yra lengvai pritaikomi ir gali padėti išspręsti daugelį svarbių problemų, tačiau šiauriniuose regionuose vis dar nepakankamai žinoma apie kukurūzų auginimo grūdams specifiką ir jų potencialų derlingumą kintančio klimato sąlygomis, todėl reikia naujų tyrimų, kurie padėtų rasti atsakymus į svarbius ūkio ir mokslo srityse kylančius klausimus.

Nors kukurūzų mineralinės mitybos pagrindai buvo suformuoti prieš keletą dešimtmečių, dauguma kukurūzų mitybos ir derliaus formavimosi eksperimentų buvo atlikti tradicinėse jų auginimo zonose, esant palankioms aplinkos sąlygoms. Nepalankiuose kukurūzų auginimui regionuose, pavyzdžiui, Lietuvoje, vis dar nežinoma, kaip suderinti kukurūzų maisto medžiagų poreikį įvairiais augimo tarpsniais su skirtingu granuliuotų organinių trąšų mineralizacijos procesu. Lietuvoje kukurūzų, auginamų grūdams, tręšimas organinėmis trąšomis nebuvo išsamiau tiriamas. Kitas pažymėtinas probleminis aspektas yra tai, kad organinių trąšų efektyvumo tyrimai daugiausia buvo skirti įvertinti ilgalaikio gausaus tręšimo poveikį, tačiau mažiau dėmesio buvo skiriama organinių trąšų, ypač granuliuotų, vienkartinio panaudojimo efektyvumui.

Šiuo metu daug eksperimentinių tyrimų atliekama spręsti specifiniams klausimams, pavyzdžiui, įvertinti įvairių naujų organinių trąšų arba jų derinių su mineralinėmis trąšomis efektyvumą (Riedell, 2014). Tačiau Šiaurės Europoje vis dar trūksta tokių eksperimentų, kai kukurūzai yra auginami nepalankiomis aplinkos sąlygomis, ir būtent tokių eksperimentų metu būtų tikėtinos reakcijos, turinčios įtakos mitybos dėsningumams. Šiuo metu yra platus spektras įvairių diagnostinių mitybos priemonių, kurios tam tikro augalo augimo tarpsniu gali, nepažeisdamos arba pažeisdamos augalą, įvertinti jo mitybos būklę. Be to, šios priemonės gali padėti įvertinti azoto išplovimo į paviršinius vandenis riziką, kuri yra ypač svarbi Baltijos regione, nes daugumoje upių ir ežerų vyrauja azoto ir fosforo junginių perteklius.

Lietuvoje kukurūzai silosui auginami daugiau nei 70 metų (Lazauskas, 1987). Anksčiau atlikti tyrimai buvo orientuoti į konkrečiam laikotarpiui aktualių klausimų sprendimą, pavyzdžiui, nustatyti tinkamą pasėlių tankumą arba tręšimo normas (Jakštaitė ir kt., 1982). Vis dėlto, šiuolaikinių veislių kukurūzus grūdams auginant vėsaus klimato sąlygomis, yra būtinos naujos žinios, siekiant iš naujo įvertinti šių augalų mitybos poreikius, kai kukurūzų tręšimui naudojamos organinės trąšos.

Hipotezė

Derinant lauko eksperimento ir modeliavimo metodus, nemoralinėje klimato zonoje galima kiekybiškai įvertinti kukurūzų derliaus potencialą ir derliaus skirtumus, atsiradusius dėl abiotinių stresų. Pakankama mityba azotu gali būti užtikrinta tręšiant amonio nitratu, taip pat jį derinant su organinėmis trąšomis, o azoto mitybos indekso ir dirvožemio mineralinio azoto kiekio analizės gali patikimai įvertinti augalo mitybos būklę stebėsenos tikslais.

Tyrimo tikslas

Atskirti ir kiekybiškai įvertinti temperatūros ir vandens streso poveikį kukurūzų derliui, įvertinti skirtingų trąšų įtaką derliaus formavimuisi ir pasiūlyti priemones, skirtas stebėti grūdams auginamų kukurūzų mitybos azotu būklę.

Tyrimo uždaviniai

1. Įvertinti AquaCrop ir AgroC modelių tinkamumą simuliuoti kukurūzų augimą bei vystymąsi ir tyrimo vietovėje apskaičiuoti derliaus potencialą.
2. Identifikuoti abiotinių stresų paplitimą ir kiekybiškai įvertinti jų įtaką derliaus sumažėjimui.

3. Ištirti skirtingų organinių trąšų, naudojamų atskirai arba kartu su amonio nitratu, įtaką biomasės kaupimuisi ir grūdų derliui.
4. Įvertinti augalų ir dirvožemio azoto rodiklių naudojimo tinkamumą, kai yra tręšiama skirtingomis trąšomis.
5. Įvertinti skirtingų trąšų azoto efektyvumą ir jų įtaką mineralinio azoto kiekiui dirvožemyje po derliaus nuėmimo.

Ginamieji teiginiai

1. AquaCrop ir AgroC modeliai nemoralinėje klimato zonoje gerai imituoja kukurūzų, auginamų grūdams, eksperimentinius duomenis, esant neribojamoms mitybos sąlygoms.
2. Vandens stresas nemoralinėje klimato zonoje pasitaiko periodiškai ir yra antrinės svarbos po temperatūros, ir tai daro įtaką esmingam kukurūzų derliaus sumažėjimui.
3. Augalų ir dirvožemio azoto rodikliai kukurūzų žydėjimo metu gali padėti tinkamai įvertinti skirtingos kilmės trąšų naudą kukurūzų grūdų produktyvumui ir dirvožemio azoto atsargoms.
4. Kukurūzams neribojamas aprūpinimas azotu gali būti užtikrintas tręšiant 170 kg ha^{-1} norma, tam naudojant amonio nitratą, paukščių mėšlą, arba amonio nitrato ir galvijų mėšlo ar žaliųjų atliekų komposto derinį.

Mokslinis naujumas

Tyrimo naujumą sudaro, tai, kad nemoralinėje klimato zonoje, siekiant ištirti kukurūzų auginimo ypatumus buvo taikyti du skirtingi metodai – lauko eksperimento ir modeliavimo. Savitas šio tyrimo aspektas yra tai, kad, panaudojus du skirtingos komplektacijos modelius, buvo kiekybiškai įvertintas kukurūzų derliaus potencialas, taip pat atskirtas temperatūros ir vandens streso poveikis kukurūzų augimui bei vystymuisi. Įrodyta, kad žemos oro temperatūros, vyraujančios kukurūzų vegetacijos metu, yra dominuojantis veiksnys, kuris daugiausiai limituoja derliaus potencialą, o vandens streso poveikis yra antrinės svarbos.

Be to, buvo įvertintas įvairių granuliuotų organinių trąšų, žaliųjų atliekų komposto ir šių trąšų derinio su mineralinėmis trąšomis efektyvumas. Siekiant optimizuoti kukurūzų, auginamų grūdams, mitybą azotu, pirmą kartą šiame regione išbandyti augalų mitybos indekso ir dirvožemio mineralinio azoto indikatoriai. Nustatyta, kad šie indikatoriai gali patikimai įvertinti kukurūzų mitybos azotu būklę.

Darbo praktinė reikšmė

Šio darbo įnašas į praktinį pritaikymą yra tai, kad, panaudojus AquaCrop ir AgroC modelius, tyrimo vietovėje buvo nustatyti pagrindiniai abiotiniai veiksniai, kurie riboja kukurūzų potencialų derlių. Gauti rezultatai padės optimizuoti kukurūzų auginimo technologijas.

Nemoralinėje klimato zonoje gauti eksperimentiniai rezultatai prisidės prie kukurūzų, auginamų grūdams, mitybos azotu optimizavimo, ypač kai yra naudojami organiniai azoto šaltiniai: granuliuotas mėšlas arba žaliųjų atliekų kompostas. Siekiant įvertinti kukurūzų mitybos N būklę, tyrime buvo sėkmingai panaudoti mitybos azotu indikatoriai, pavyzdžiui, SPAD, todėl šiame regione juos galima rekomenduoti platesniam praktiniam panaudojimui.

Tyrimo rezultatų aprobavimas

Parengtos dvi publikacijos žurnaluose, įrašytuose į duomenų bazę *Clarivate Analytics Web of Science*. Gauti tyrimo rezultatai buvo pristatyti penkiose tarptautinėse konferencijose.

Disertacijos darbo aprašas

Disertacinis darbas parašytas anglų kalba. Disertacijos apimtis – 123 puslapiai. Disertaciją sudaro santrauka, įvadas, literatūros apžvalga, metodika, rezultatai, diskusija, išvados, literatūros sąrašas ir publikacijų sąrašas. Buvo panaudotos 23 lentelės, 19 paveikslų, 187 literatūros šaltiniai.

TYRIMŲ METODIKA

Siekiant atsakyti į tyrimo klausimus buvo taikyti du skirtingi tyrimo metodai: lauko eksperimentai ir modeliavimas. Vykdant lauko eksperimentus buvo siekiama įvertinti skirtingų trąšų poveikį kukurūzų produktyvumui, be to, šie duomenys buvo panaudoti kaip modelių įvesties parametrai. Modeliavimo metodas buvo pasirinktas siekiant įvertinti žemos oro temperatūros ir vandens streso poveikį kukurūzų grūdų derliui.

Tyrimo vieta

Lauko eksperimentai su kukurūzais buvo atlikti 2015–2017 m. Lietuvos agrarinių ir miškų mokslų centro filiale Žemdirbystės institute (55°39′ Š, 23°86′ R). Tai intensyvios augalininkystės regionas. Pagal Köppen’o klimato klasifikaciją (Kottek ir kt., 2006), tyrimo vietovės klimatas klasifikuojamas kaip *Dfb* – drėgnas kontinentinis su šiltomis vasaromis, tačiau gana šaltais žiemos periodais. Pagal Europos gamtinę klasifikaciją, Lietuva yra Europos nemoralinėje klimato zonoje, kurios klimatas yra apibūdinamas kaip žemyninis, vėsus, o augalų vegetacijos sezonas gana trumpas. Šiai klimato zonai taip pat priskiriamos ir Pietvakarių Estijos, Latvijos ir Šiaurės Vakarų Baltarusijos teritorijos (Metzger ir kt., 2012). Vidutinė metinė oro temperatūra yra 7° C, vidutinis kritulių kiekis – 557 mm (vidurkis per 30 metų laikotarpį, t. y. nuo 1981 iki 2010 m.). Tyrimo vietovėje vyrauja karbonatingas giliau stagniškas išplautžemis (IDj2-k) (LTDK-99); granuliometrinė sudėtis – smėlingas lengvas priemolis. Dirvožemio ariamojo sluoksnio (0–20 cm) pH_{KCL} artimas neutraliam (6,20–6,85), jame santykinai mažai organinių medžiagų ir vidutiniškai augalų pasiekiamo fosforo ir kalio. Mineralinio azoto (N_{min}) kiekis 0–60 cm gylyje, priklausomai nuo metų, skyrėsi esmingai: nuo 10,7 mg kg^{-1} (2017 m.) iki 20,7 mg kg^{-1} (2016 m.).

Eksperimento variantai ir agrotechnika

2015–2017 metais lauko eksperimentai vykdyti su trumpos vegetacijos hibridinės veislės Agiraxx kukurūzais (FAO skaičius – 190). Ši veislė sukurta Prancūzijoje, RAGT sėklininkystės firmoje. Veislės Agiraxx kukurūzai pasižymi tuo, kad anksti subrandina derlių, todėl yra tinkami auginti šiame regione. Kukurūzai buvo pasėti dirvožemio temperatūrai pasiekus 8–10° C, 6–7 cm gyliu įterpus 70 000 ha^{-1} sėklų (atstumas tarp eilučių – 0,75 m, atstumas tarp augalų – 0,18 m). Trąšos buvo išbertos rankiniu būdu, po to įterptos į dirvožemį priešsėjinio dirvos dirbimo metu. Piktžolės naikintos herbicidu MAISTER OD (norma 1,7 l ha^{-1}). Kukurūzų derlius buvo nuimtas rankiniu būdu po pirmųjų rudens šalnų. Prieš sėją kukurūzai buvo patręšti 170 kg ha^{-1} N, naudojant amonio nitratą (AN170), granuliuotą galvijų mėšlą (PCM), granuliuotą paukščių mėšlą (PPM), žaliųjų atliekų kompostą (GWC) arba AN ir organinių trąšų derinį (AN + PCM, AN + PPM bei AN + GWC). Papildomai buvo įrengti šie trys variantai: (1) kontrolinis – be trąšų (CON), (2) amonio nitratas 90 kg ha^{-1} (AN90), (3) amonio nitratas 90 kg ha^{-1} + PK (AN1) (planuojamam derliui). Eksperimento variantai išdėstyti rendomizuotai, kartoti keturis kartus, visas laukelio plotas – 30 m^2 (ilgis – 10 m, plotis – 3 m). Galutiniam derliui nustatyti buvo panaudotos dvi vidurinės eilės (12 m^2).

Eksperimente naudotas granuliuotas galvijų mėšlas ir žaliųjų atliekų kompostas buvo pagamintas vietinių gamintojų ir yra parduodamos rinkoje. Granuliuotas galvijų mėšlas pagamintas iš kraikinio galvijų mėšlo, kuris kompostavimo metu buvo papildomai džiovinamas iki tinkamo sausumo, reikalingo granuliavimo procesui. Granuliuoto paukščių mėšlo gamybos procesas panašus: mėšlas buvo biologiškai fermentuotas, tada brandintas specialiose saugojimo aikštelėse, vėliau susmulkintas ir kompostuotas. Žaliųjų atliekų kompostas buvo pagamintas iš biodegraduojančių (augalinių) atliekų. Šios atliekos buvo kompostuojamos ilgiau nei 60 dienų specialiose saugojimo aikštelėse.

Augalų matavimai

Kukurūzų vystymosi tarpsniai buvo nustatomi pagal „Leaf Collar“ metodiką, kurioje pagrindiniai kukurūzų vystymosi tarpsniai skirstomi į vegetatyvinius (V) ir reprodukcinius (R) periodus (Abendroth ir kt., 2011). Tarpsniai buvo registruojami, kai daugiau nei 50 % augalų pasiekdavo tam tikrą tarpsnį. Biomasei nustatyti augalų ėminiai buvo atrenkami 5 kartus per vegetaciją (V8, V14, VT/R1, R3 tarpsniais), po 5 augalus iš kiekvieno laukelio (20 iš varianto). Kiekvienas augalas buvo padalintas į šias pagrindines dalis: lapai, stiebas, burbuolė, žiedynas ir grūdai. Kukurūzams pasiekus fiziologinę brandą, t. y. kai ant grūdo prisegimo prie burbuolės vietos pasirodė juodas taškas, iš dviejų vidurinių eilučių (8 × 1,5 = 12 m^2) buvo paimti ėminiai, siekiant nustatyti bendrą antžeminės dalies biomasę ir grūdų derlių. Įvairios kukurūzų dalys buvo pasvertos ir džiovintos 65 ± 5 °C temperatūroje iki pastovios sausos masės. Lapų plotas matuotas 5 kartus per vegetaciją, naudojant nešiojamą matuoklį (CID ® Inc., WA, USA), o pagal gautus rezultatus buvo apskaičiuotas lapų ploto indeksas. Modelių įvesties parametrams lapų ploto indeksas buvo perskaičiuotas į lapijos dangą (CC) (dirvožemio padengimas lapais, kuris išreikštas %) naudojantis šia lygtimi (Hsiao ir kt, 2009):

$$CC = 100{,}5\,[1 - \exp(-0{,}60\ LAI)]^{1.2}.$$

Kukurūzų mitybos azotu būklės vertinimas

Biomasės ėminiai, paimti kukurūzų V8, VT ir R6 vystymosi tarpsniais, buvo naudojami cheminėms analizėms. Kukurūzų V8 ir VT vystymosi tarpsniais N, P ir K koncentracija buvo nustatyta visame augale, o R6 tarpsniu – atskirai grūduose ir likusioje biomasėje. Azoto kiekis biomasėje ir grūduose buvo nustatytas Kjeldalio metodu. Azoto įsisavinimas biomasėje ir grūdų derliuje buvo apskaičiuotas padauginus azoto koncentraciją ir kukurūzų derlių. Azoto mitybos indeksas (NNI) buvo apskaičiuotas biomasės azoto koncentraciją padalinant iš kritinės azoto koncentracijos (Lemaire ir Meynard, 1997):

$$NNI = N_{\text{išmatuotas}} / N_{\text{kritinis}},$$

kai NNI = 1, mityba laikoma optimalia, o kai NNI > 1 arba NNI < 1, mityba azotu laikoma pertekline arba nepakankama.

Skirtingų trąšų efektyvumui apskaičiuoti buvo panaudotas agronominis azoto efektyvumo koeficientas (AE_N) (Dobermann, 2005):

$$AE_N = (Y_N - Y_0) / F_N .$$

Dalinis azoto panaudojimo efektyvumas (PFP_N) buvo apskaičiuotas pagal formulę (Dobermann, 2005):

$$PFP_N = Y_N / F_N .$$

Augalų azoto koeficientas (RE_N) buvo apskaičiuotas pagal formulę (Dobermann, 2005):

$$RE_N = (U_N - U_0) / F_N .$$

kai Y_N – kukurūzų derlius panaudojus azoto trąšas (kg ha^{-1}), Y_0 – kukurūzų derlius nenaudojant trąšų (kg ha^{-1}), F_N – tręšimo norma (kg ha^{-1}), U_N – suminis azoto kiekis kukurūzų biomasėje panaudojus azoto trąšas (kg ha^{-1}), U_0 – suminis azoto kiekis kukurūzų biomasėje nenaudojant trąšų (kg ha^{-1}).

Chlorofilo indeksas buvo matuojamas periodiškai nešiojamu SPAD-502 chlorofilo matuokliu (Minolta, Ramsey, NJ, JAV) šiais augimo tarpsniais: V5, V14, VT, R2 ir R3. Kiekviename laukelyje atsitiktine tvarka buvo pamatuota 10 augalų (matuotas jauniausias galutinai išsiskleidęs lapas).

Dirvožemio agrocheminės ir hidraulinės savybės

Kiekvienais metais prieš kukurūzų sėją iš dirvožemio ariamojo sluoksnio (0–20 cm) atrinktuose ėminiuose buvo nustatyta pH_{KCl}, humuso, suminio azoto, judriojo fosforo ir kalio kiekiai. Mineraliniam azotui ($N\text{-}N0_3$ + $N\text{-}NH_4$) nustatyti dirvožemio ėminiai buvo paimti iš 0–30 ir 31–60 cm gylio intensyvaus augimo metu ir po derliaus nuėmimo. Mineralinis azotas (N_{min}) buvo nustatytas spektrometriniu metodu. Visos dirvožemio ir augalų cheminės analizės buvo atliktos Lietuvos agrarinių ir miškų mokslų centro filialo Agrocheminių tyrimų laboratorijoje.

Siekiant nustatyti dirvožemio hidraulines savybes, 2017 m. eksperimento vietovėje iš dirvožemio pagrindinių horizontų: 15–20, 40–45, 70–75, 90–95 ir 120–125 gylio, buvo paimta 10 nesuardytos struktūros dirvožemio ėminių (vieno ėminio dydis – 250 cm^3). Paimti ėminiai buvo nuvežti į Jülich tyrimų centrą Vokietijoje tolesnėms analizėms. Dirvožemio hidraulinės savybės buvo nustatytos taikant HYPROP metodą (UMS, München, Vokietija), aprašytą Schindler ir kt. (2010). Dirvožemio hidraulinis laidumas (K_{sat}) buvo nustatytas naudojantis KSAT sistema (München, Vokietija). Šiame tyrime skirtumas tarp maksimalios dirvožemio drėgmės ir augalų vytimo ribos yra apibūdinimas kaip augalų pasiekiamos drėgmės kiekis.

Dirvožemio drėgmės matavimai

Tyrimo metais (2015–2017 m.) dirvožemio drėgmė buvo matuota periodiškai 0–10 cm gylyje naudojant TRIME-FM2 matuoklį (IMKO, GmbH, Ettlingen Vokietija). Papildomai dirvožemio drėgmė buvo matuota 30 ir 60 cm gylyje naudojant irometrus (Irrometer Company, Riverside, CA, JAV).

Meteorologinės sąlygos

Kasdieniai meteorologiniai duomenys: maksimali, minimali ir vidutinė temperatūra, kritulių kiekis, santykinis drėgnumas, vėjo greitis 2 m aukštyje, saulės spindėjimo laikas, buvo gauti iš Dotnuvos meteorologijos stoties, kuri priklauso Lietuvos hidrometeorologijos tarnybai prie Aplinkos ministerijos. Meteorologiniai duomenys buvo panaudoti apskaičiuoti evotranspiracijai (ET_0), kaip aprašyta Allen ir kt. (1998). Tyrimo metu (2015–2017 m.) gauti meteorologiniai duomenys buvo palyginti su 30-ies metų (1981–2010 m.) klimato normos vidurkiu. Efektyvių temperatūrų suma (GDD) kukurūzams buvo apskaičiuota bazinę temperatūrą (8° C) atimant iš vidutinės oro temperatūros.

Tyrimo duomenų statistinė analizė

Statistinis trejų metų grūdų derliaus, azoto kiekio augaluose ir dirvožemio mineralinio azoto duomenų apdorojimas atliktas dispersinės analizės metodu, aprašytu Petersen (1994). Esminiai skirtumai tarp variantų buvo nustatyti Tukey’s testu, taikant 95 % patikimumo lygmenį. Koreliaciniai ryšiai tarp derliaus ir augalų rodiklių įvertinti tiesinės regresijos lygtimis. Statistinis duomenų įvertinimas atliktas statistine programa *SAS 9.4* (SAS Institute, 2016).

Modelių aprašymas

AquaCrop modelis skirtas simuliuoti įvairių žemės ūkio augalų derliaus formavimosi etapus. Šis modelis galutinį augalų derlių apskaičiuoja keturiais pagrindiniais žingsniais: 1) simuliuojant augalų augimą ir vystymąsi, 2) simuliuojant augalų transpiraciją, 3) simuliuojant biomasės derlių ir 4) simuliuojant grūdų derlių (Raes ir kt., 2017). Išsamus modelio aprašymas yra pateiktas jo kūrėjų (Raes ir kt., 2009; Hsiao ir kt., 2009; Steduto ir kt., 2009). Šio tyrimo metu buvo panaudota AquaCrop modelio 6.0 versija. AquaCrop modelio veikimo principas paremtas vandens balanso lygties pagrindu, todėl dažniausiai yra taikomas sprendžiant įvairias problemas, susijusias su drėkinimo planavimu arba drėgmės trūkumu.

AgroC susideda iš trijų skirtingų modelių: SoilCO2 (Šimůnek ir Suarez, 1993), RothC (Coleman ir Jenkinson, 2008) ir SUCROS (Spitters ir kt., 1989). Išsamų AgroC modelio veikimo aprašymas yra pateiktas jo kūrėjų darbuose (Herbst ir kt., 2008; Klosterhalfen ir kt., 2017). Esminis skirtumas tarp AgroC ir AquaCrop modelių yra tai, kad, atsižvelgiant į mokslinių tyrimų poreikį, visi parametrai AgroC modelyje, susiję su dirvožemiu ir augalų augimu, gali būti keičiami.

Modelių kalibravimas ir patikrinimo procedūros

Siekiant užtikrinti augimo neribojančias azoto mitybos sąlygas, kukurūzų augimo modeliavimui buvo pasirinktas variantas su mineralinėmis trąšomis (AN170). Modeliai buvo kalibruojami panaudojus 2015 m. eksperimentinius duomenis, o 2016 m. rezultatai buvo panaudoti modelių tikrinimui. AgroC modelis buvo kalibruojamas naudojant dviejų žingsnių procedūrą (Klosterhalfen ir kt., 2017). Pirmiausia buvo koreguoti parametrai, apibūdinantys kukurūzų augimą ir vystymąsi, po to tie, kurie apibūdina eksperimento vietos dirvožemį. AquaCrop modelyje pirmiausia buvo įvesti parametrai, nusakantys lapų ploto vystymąsi (augalų tankumas, sudygimo greitis), vėliau koreguotas laikas, kada augalai pasiekia tam tikrą augimo tarpsnį (efektyvių temperatūrų suma sudygimui, maksimaliam lapų plotui, senėjimui ir fiziologinei brandai). Paskutiniame etape koreguoti koeficientai, nusakantys augalų evotranspiraciją, drėgmės panaudojimo produktyvumą ir derliaus indeksą. Modeliuojant potencialų grūdų derlių buvo daroma prielaida, kad visi veiksniai, pavyzdžiui, oro temperatūra, drėgmės kiekis dirvožemyje, tręšimas ir agrotechninės technologijos, neribojo potencialaus kukurūzų augimo. Papildomai buvo modeliuota, kiek temperatūros ir drėgmės stygius riboja kukurūzų derlių.

REZULTATAI

Modelių kalibravimas ir patikrinimas

Biomasės ir grūdų derlius. Abu šio tyrimo metu panaudoti modeliai gana gerai simuliavo biomasės priaugimą (1 lentelė).

1 lentelė. Kukurūzų faktinių ir simuliuotų verčių palyginimo statistiniai rodikliai kalibravimo (2015) bei patikrinimo (2016) metais.

Rodiklis	Faktinė vertė	Simuliuota vertė		RMSE		R^2	
		AgroC	AquaCrop	AgroC	AquaCrop	AgroC	AquaCrop
Kalibravimo metai							
Lapijos danga (%)				11,7	7,02	0,71	0,99
Biomasė (t ha^{-1})	14,53±0,6	15,27	14,05	0,86	0,69	0,97	0,98
Lapai (t ha^{-1})	1,21±0,2	1,99	–	0,53	–	0,69	–
Stiebai (t ha^{-1})	2,37±0,2	3,54	–	0,79	–	0,56	–
Burbuolė, žiedynas (t ha^{-1})	4,1±0,4	2,81	–	0,96	–	0,95	–
Grūdų derlius (t ha^{-1})	6,85±0,6	6,93	6,90	0,44	1,01	0,98	0,92
Dirvožemio drėgmė 10 cm gylyje (cm^3 cm^{-3})				0,023	0,032	0,61	0,52
Dirvožemio drėgmė 30 cm gylyje (cm^3 cm^{-3})				0,016	0,021	0,48	0,41
Dirvožemio drėgmė 60 cm gylyje (cm^3 cm^{-3})				0,026	0,012	0,58	0,78
Patikrinimo metais							
Lapijos danga (%)				17,02	4,01	0,76	0,97
Biomasė (t ha^{-1})	18,52±0,7	18,97	18,02	0,54	1,33	0,99	0,97
Lapai (t ha^{-1})	2,26±0,2	2,51	–	0,68	–	0,86	–
Stiebai (t ha^{-1})	4,56±0,4	4,52	–	0,42	–	0,91	–
Burbuolė, žiedynas (t ha^{-1})	2,68±0,4	2,93	–	0,61	–	0,31	–
Grūdų derlius (t ha^{-1})	9,02±0,7	9,01	8,93	0,35	0,89	0,99	0,98
Dirvožemio drėgmė 10 cm gylyje (cm^3 cm^{-3})				0,031	0,056	0,78	0,53
Dirvožemio drėgmė 10 cm gylyje (cm^3 cm^{-3})				0,018	0,023	0,69	0,66
Dirvožemio drėgmė 10 cm gylyje (cm^3 cm^{-3})				0,017	0,019	0,54	0,55

Statistiniai rodikliai parodė, kad AquaCrop modelis 2015 m. (vėsiais ir sausais) biomasės prieaugį vegetacijos laikotarpiu simuliavo šiek tiek geriau (RMSE = 0,69 t ha^{-1}; $R^2 = 0,98$, $p < 0,01$) nei AgroC modelis (RMSE = 0,86 t ha^{-1}; $R^2 = 0.97$, $p < 0,01$). Tačiau 2016 m. (šiltais ir drėgnais) AgroC modelis geriau simuliavo biomasės prieaugį (RMSE = 0,54 t ha^{-1}; $R^2 = 0,99$, $p < 0,01$) nei AquaCrop modelis (RMSE = 1,33 t ha^{-1}; $R^2 = 0,97$, $p < 0,01$). 2015 m. faktinis biomasės sausųjų medžiagų derlius buvo 14,53 ±

0,65, AquaCrop modelis simuliavo šiek tiek mažesnį – 14,05 t ha^{-1}, AgroC didesnį derlių – 15,27 t ha^{-1}. Kukurūzų augimui ir vystymuisi palankesniais 2016 m. buvo gautas gana didelis biomasės derlius – 18,52 ± 0,75 t ha^{-1}, AquaCrop modelis vėl simuliavo mažesnį – 18,02 t ha^{-1}, AgroC didesnį – 18,97 t ha^{-1} derlių.

Lauko eksperimentuose 2015 m. gauta 6,85 t ha^{-1}, 2016 m. – 9,02 t ha^{-1} grūdų. Šie akivaizdūs skirtumai iš dalies susidarė dėl nevienodo temperatūros ir drėgmės režimo, kuris ypač svarbus kukurūzus auginant šioje klimato zonoje. AgroC modelis modeliavo šiek tiek didesnį grūdų derlių (2015 m. – 6,93 t ha^{-1}, 2016 m. – 9,01 t ha^{-1}) nei AquaCrop modelis (2015 m. – 6,90 t ha^{-1}, 2016 m. – 8,93 t ha^{-1}). Nepaisant to, kad modelių kalibravimo (2015 m.) ir patikrinimo (2016 m.) metais susidarė gana kontrastingos aplinkos sąlygos, abu modeliai labai gerai simuliavo biomasės ir grūdų derlių.

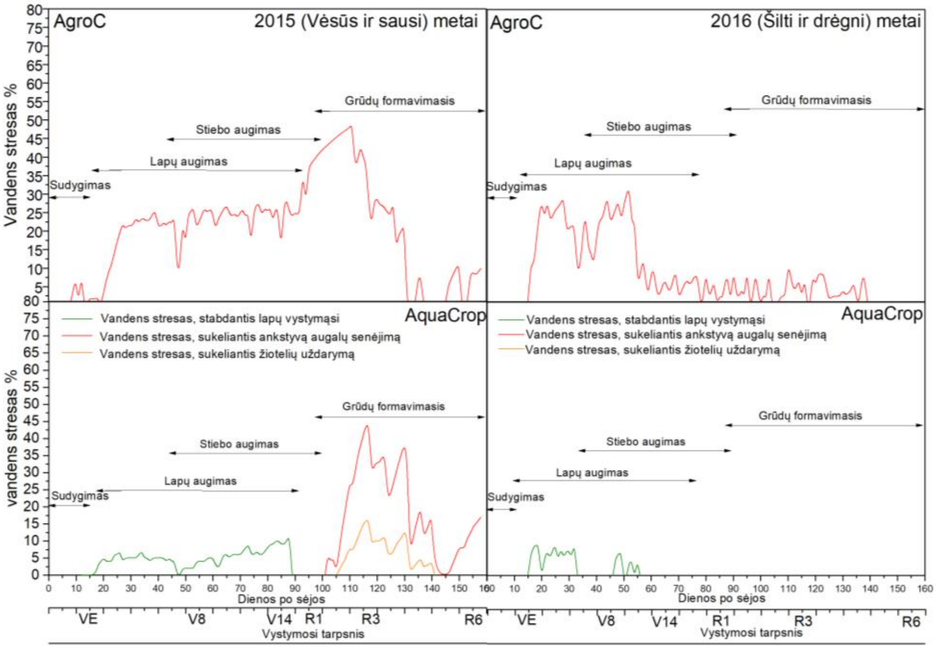
Lapijos dangos vystymasis. Specifinė AquaCrop modelio savybė yra ta, kad jis nesimuliuoja lapų ploto indekso, o šis indeksas yra pakeistas kitu parametru – lapijos danga. Šis parametras parodo, kokia procentinė dalis dirvožemio yra uždengta lapijos. Siekiant gauti palyginamus rezultatus, AgroC modelio simuliuotas lapų ploto indeksas buvo perskaičiuotas į procentinę lapijos dangos dalį. Vėsaus klimato zonoje kukurūzų lapijos formavimasis yra ganėtinai specifinis, tai yra kukurūzai turi mažiau lapų ir jų lapų plotas yra mažesnis nei šilto klimato zonose. Todėl, siekiant gauti gerus simuliuotus rezultatus, abiejų modelių specifiniai parametrai, lemiantys lapijos formavimąsi ir vystymąsi, buvo gerokai koreguoti.

Apibendrinant eksperimento rezultatus galima teigti, kad abu naudoti modeliai gerai simuliavimo lapijos dangos formavimąsi, pavyzdžiui, 2015 ir 2016 metais gautos RMSE reikšmės AquaCrop modelio buvo atitinkamai 7,02 ir 4,01 % (R^2 = 0,99 ir 0,97, $p < 0,01$), o AgroC modelio buvo šiek tiek didesnės – 11,7 % ir 17,02 % (R^2 = 0,71–0,76, $p < 0,01$) (1 lentelė).

Dirvožemio drėgmės variacija. Palyginus 2015 ir 2016 metais gautus faktinius rezultatus su simuliuotais galima teigti, kad AgroC modelis geriau simuliavo dirvožemio drėgmės variaciją 10 ir 30 cm gylyje nei AquaCrop modelis (1 lentelė). Reikėtų atkreipti dėmesį, kad abu modeliai ne visai tiksliai užfiksavo kai kuriuos dirvožemio drėgmės pikus gilesniame (60 cm) sluoksnyje. 2015 metais (sausais) vegetatyvinio periodo metu (VE–V8 vystymosi tarpsniu) AquaCrop modelis simuliavo didesnes dirvožemio drėgmės reikšmes, o reprodukcinio periodo metu (R1–R2 vystymosi tarpsniu) mažesnes, o AgroC modelis per visą auginimo sezoną simuliavo didesnes reikšmes. 2015 m. AgroC modelio apskaičiuota paklaida (RMSE) tarp matuotų ir simuliuotų dirvožemio drėgmės rezultatų buvo gana maža: 10 cm gylyje – 0,023 cm^3 cm^{-3}, 30 cm gylyje – 0,016 cm^3 cm^{-3}, 60 cm gylyje – 0,026 cm^3 cm^{-3}; 2016 m. atitinkamos reikšmės buvo didesnės: 10 cm – 0,031 cm^3 cm^{-3}, 30 cm – 0,018 cm^3 cm^{-3}, 60 cm – 0,017 cm^3 cm^{-3}. AquaCrop modelio apskaičiuotos RMSE reikšmės buvo didesnės abiem metais. Koreliacinė-regresinė analizė parodė esminį ryšį (AquaCrop – R^2 = 0,41–0,78, AgroC – R^2 = 0,48–0,78) tarp simuliuotos ir matuotos dirvožemio drėgmės variacijos.

Apibendrinant šiuos rezultatus galima teigti, kad dirvožemio drėgmės variaciją geriau simuliavo AgroC modelis nei AquaCrop.

Temperatūros ir vandens stresas kukurūzų vegetacijos laikotarpiu. AquaCrop ir AgroC modelių simuliuotas drėgmės stresas parodytas 1 paveiksle. 2015 m. kukurūzų vegetatyvinio (iki žydėjimo) periodo metu iškrito 126,8 mm kritulių, todėl vandens trūkumas buvo nedidelis. AquaCrop modelio simuliuoti vandens streso rezultatai parodė, kad tuo metu jis svyravo 0–12 %, o AgroC modelis prognozavo didesnes reikšmes, tai yra iki 27 %. Kritulių kiekis reprodukcinio (nuo žydėjimo iki fiziologinės brandos) periodo metu buvo tik 67,4 mm, ir tai turėjo įtakos santykinai dideliam kukurūzų vandens trūkumui. Abu modeliai didžiausią vandens stresą apskaičiavo grūdų formavimosi metu: AquaCrop – 42 %, AgroC – 49 %. 2016 m. iškritusių kritulių kiekis viso kukurūzų auginimo ciklo metu buvo pakankamas (vegetatyvinio periodo metu – 211 mm, reprodukcinio periodo metu – 167,4 mm), todėl vandens trūkumas buvo nežymus. Per visą vegetacijos laikotarpį su AquaCrop modeliu apskaičiuotas vandens stresas daugiausia vyravo vegetacijos pradžioje, bet nebuvo didesnis nei 11 %, o AgroC modelis simuliavo šiek tiek didesnį vandens trūkumą, kuris svyravo nuo 2 iki 30 %.

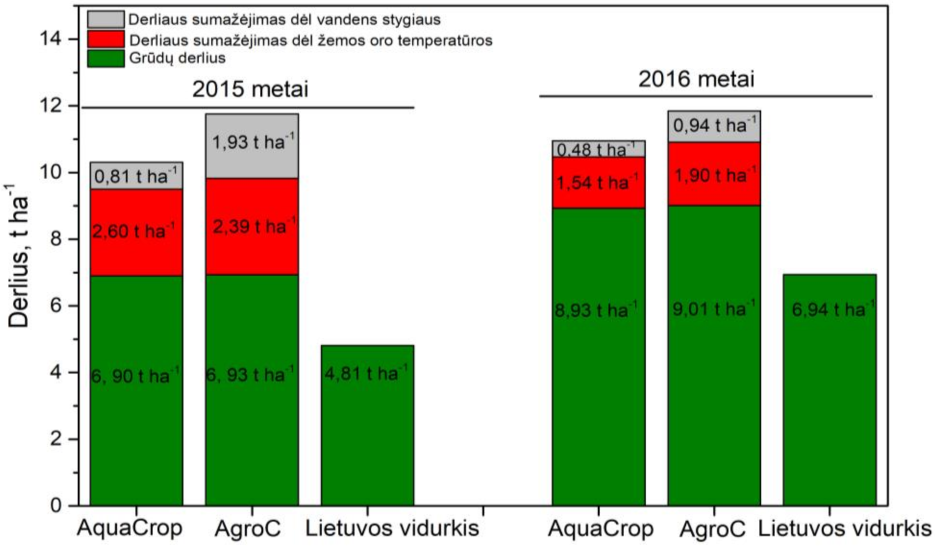


1 paveikslas. AquaCrop ir AgroC modeliais apskaičiuotas vandens trūkumas kontrastingais tyrimo metais

2015 m. abu modeliai nurodė reikšmingą derliaus sumažėjimą dėl vandens trūkumo: AquaCrop – 0,81 t ha^{-1}, AgroC – 1,93 t ha^{-1} (2 paveikslas). Kukurūzams palankiais 2016 m. vandens trūkumas mažino derlių, tačiau perpus mažiau nei 2015 m.: AquaCrop – 0,48 t ha^{-1}, AgroC – 0,94 t ha^{-1}.

2015 m. žemos oro temperatūros (<8° C) vegetatyvinio periodo metu sudarė 28,2 %, o reprodukcinio periodo metu – 24,6 %. AquaCrop modelis apskaičiavo, kad 2015 m. dėl nepalankių oro temperatūrų derlius sumažėjo 2,60 t ha^{-1}; panašų sumažėjimą nurodė ir AgroC modelis – 2,39 t ha^{-1}. 2016 m. oro temperatūra kukurūzų auginimo metu buvo aukštesnė, palyginus su 2015 m., todėl potencialaus grūdų derliaus sumažėjimas taip pat buvo mažesnis: AquaCrop – 1,54 t ha^{-1}, AgroC – 1.90 t ha^{-1}.

Apibendrinant eksperimento rezultatus galima teigti, kad 2015 m. vandens ir temperatūros stresai potencialų grūdų derlių sumažino 3,41 t ha^{-1} (AquaCrop) ir 4,32 t ha^{-1} (AgroC), o 2016 m. derliaus sumažėjimas dėl šių veiksnių buvo mažesnis: AquaCrop – 2,02 t ha^{-1}, AgroC – 2,84 t ha^{-1}.



2 paveikslas. Simuliuotas potencialus kukurūzų grūdų derlius ir jo sumažėjimas dėl žemos oro temperatūros ir vandens stygiaus 2015 ir 2016 metais

Apibendrinimas. Remiantis vien lauko eksperimentiniais duomenimis gana sudėtinga nustatyti žemų oro temperatūrų ir vandens stygiaus įtaką kukurūzų grūdų derliui, nors modeliuoti rezultatai rodo, kad abu šie veiksniai yra reikšmingi, tačiau žemos oro temperatūros yra svarbiausias abiotinis veiksnys, ribojantis kukurūzų augimą ir vystymąsi šiame regione. Gauti rezultatai sutampa ir su kitų mokslininkų atliktų tyrimų duomenimis, kad Šiaurės Europoje žemos oro temperatūros esmingai riboja kukurūzų augimą ir labiausiai pasireiškia ankstyvą pavasarį, o sausringi periodai taip pat kelia susirūpinimą vietiniams ūkininkams (Olesen ir kt., 2011).

Šio tyrimo metu modeliai buvo panaudoti siekiant įvertinti žemų oro temperatūrų įtaką grūdų derliui, tačiau šio streso poveikis atskiroms augalų dalims (lapams, stiebams) nebuvo vertintas. 2015 ir 2016 metais skirtumas tarp Lietuvos ūkininkų vidutinių derlių buvo 31 % (2 paveikslas); šie rezultatai sutapo su eksperimentuose skirtingais metais gautais derliaus skirtumais.

Pažymėtina, kad abu modeliai buvo kalibruojami rankiniu būdu, todėl šiuo atveju gauti modeliuoti rezultatai yra iš dalies subjektyvūs, nes priklauso nuo naudotojo sprendimų (Diekkrüger ir kt., 1995). Palyginus abu modelius galima teigti, kad AquaCrop šiek tiek geriau simuliavo lapijos dangą / lapų ploto indeksą, o AgroC geriau apskaičiavo dirvožemio drėgmės variaciją. Be to, AgroC modelis suteikia papildomos informacijos apie atskirų augalo dalių augimą ir vystymąsi, tačiau, siekiant ją gauti, reikia papildomų įvesties duomenų. Sprendimas, kokį modelį naudoti (paprastesnį ar sudėtingesnį) dažnai priklauso nuo turimų eksperimentinių duomenų kiekio ir kokybės.

Tyrimo metais lauko eksperimentuose periodiškai buvo atliekami išsamūs augalų ir dirvožemio matavimai, todėl buvo sukauptas pakankamai didelis kiekis duomenų. Tai leido panaudoti ir palyginti du skirtingos komplektacijos modelius. Sudėtingi ir lankstūs modeliai, pavyzdžiui, AgroC, leidžia analizuoti įvairias aplinkos sąlygas ir jų įtaką augalams. Šioje studijoje gauti rezultatai taip pat patvirtino, kad AquaCrop modelis gali būti efektyviai naudojamas siekiant geriau suprasti pagrindinius augalo fiziologinius mechanizmus, kai augimas ir vystymasis ribojamas vandens stygiaus ar žemos oro temperatūros. Abu panaudoti modeliai parodė, kad nemoralinėje klimato zonoje svarbesnis ribojantis veiksnys yra žema oro temperatūra nei vandens trūkumas. Tačiau šių veiksnių įtaka kukurūzų augimui ir vystymuisi priklauso nuo pasirinkto modeliavimo metodo. Pavyzdžiui, AgroC modelio apskaičiuotas drėgmės stresas priklauso nuo apskaičiuotos potencialios evotranspiracijos, o ją lemia skirtingi pasirenkami augalų koeficientai, taip pat ir dirvožemio hidraulinės savybės. Žemos temperatūros poveikis kukurūzų augimui priklauso nuo pasirinktos bazinės oro temperatūros. Abu modeliai skiriasi savo komplektacija, tačiau, nepaisant to, gerai simuliavo kukurūzų augimą ir vystymąsi, o tai suteikia pasitikėjimo gautais rezultatais, kurie, taikant skirtingus metodus, buvo panašūs.

Skirtingų trąšų poveikis kukurūzų mitybos azotu būklei ir biomasės formavimuisi vegetatyvinio periodo metu

Kukurūzų augimą ir vystymąsi galima suskirstyti į du pagrindinius tarpsnius: vegetatyvinį ir reprodukcinį. Vegetatyvinio periodo metu kukurūzai formuoja lapiją, stiebus ir reprodukcinius organus. Nustatyta, kad vegetatyvinio periodo metu kukurūzai sukaupia didžiąją dalį maisto medžiagų: 2/3 azoto, 1/3 fosforo ir 4/5 kalio, todėl šioje stadijoje bet koks maisto medžiagų, vandens ar temperatūros stresas mažina potencialų grūdų derlių.

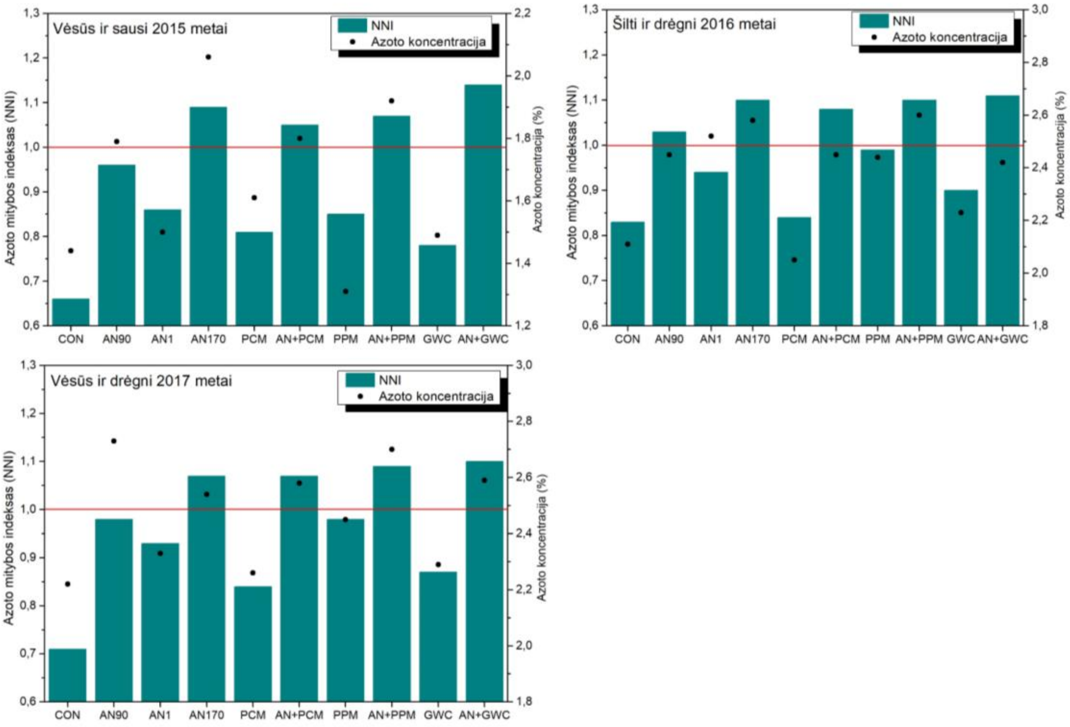
Kukurūzų mitybos būklė ir dirvožemio mineralinio azoto kiekis žydėjimo metu

Biomasė. Kukurūzų žydėjimo metu (VT tarpsniu) biomasė 2015 m. svyravo nuo 4,09 iki 6,99 t ha^{-1}, 2016 m. – nuo 4,68 iki 6,18 t ha^{-1}, 2017 m. – nuo 5,09 iki 6,78 t ha^{-1}. Organinėmis trąšomis (išskyrus GWC) patręštuose laukeliuose biomasės buvo sukaupta 11,7 %, o variantuose su organinių ir mineralinių trąšų deriniu – 24,6 % daugiau nei netręštuose kontroliniuose.

Lapų ploto indeksas (LAI). Tyrimo metais kukurūzai didžiausią LAI formavo jų žydėjimo metu: 2015 m. – 2,8, 2016 m. – 2,8, 2017 m. – 2,9. Sąlygiškai mažą maksimalų LAI (nesiekė 3) galima paaiškinti tuo, kad auginti trumpos vegetacijos veislės kukurūzai suformavo tik iki 14 lapų, o tradiciniuose auginimo regionuose kukurūzų hibridai formuoja iki 20 lapų (Abendroth ir kt., 2011). Daugelis studijų parodė, kad LAI priklauso ne tik nuo veislės, bet ir nuo kitų veiksnių, pavyzdžiui, sėjos laiko, auginimo vietos arba azoto koncentracijos augale.

Chlorofilo indeksas (SPAD). Kukurūzų auginimo drėgnais sezonais (2016 ir 2017 m.) SPAD reikšmių variacija buvo mažesnė nei sausais (2015 m.). Nepaisant skirtingų metų įtakos, gauti rezultatai leido išskirti dvi grupes: didesnės SPAD reikšmės nustatytos AN170, AN + PCM, AN + PPM, AN + GWC, AN90, AN1 ir PPM, variantuose, mažesnės – PCM, GWC ir CON variantuose.

Azoto koncentracija ir azoto mitybos indeksas (NNI). Kukurūzų vidutinė azoto koncentracija 2015 m. buvo 1,7 %, 2016 m. – 2,4 % ir 2017 m. – 2,5 %. Gauti skirtumai turėjo įtakos ir apskaičiuoto azoto mitybos indekso (NNI) pokyčiams 2015–2017 metų laikotarpiu (3 paveikslas).



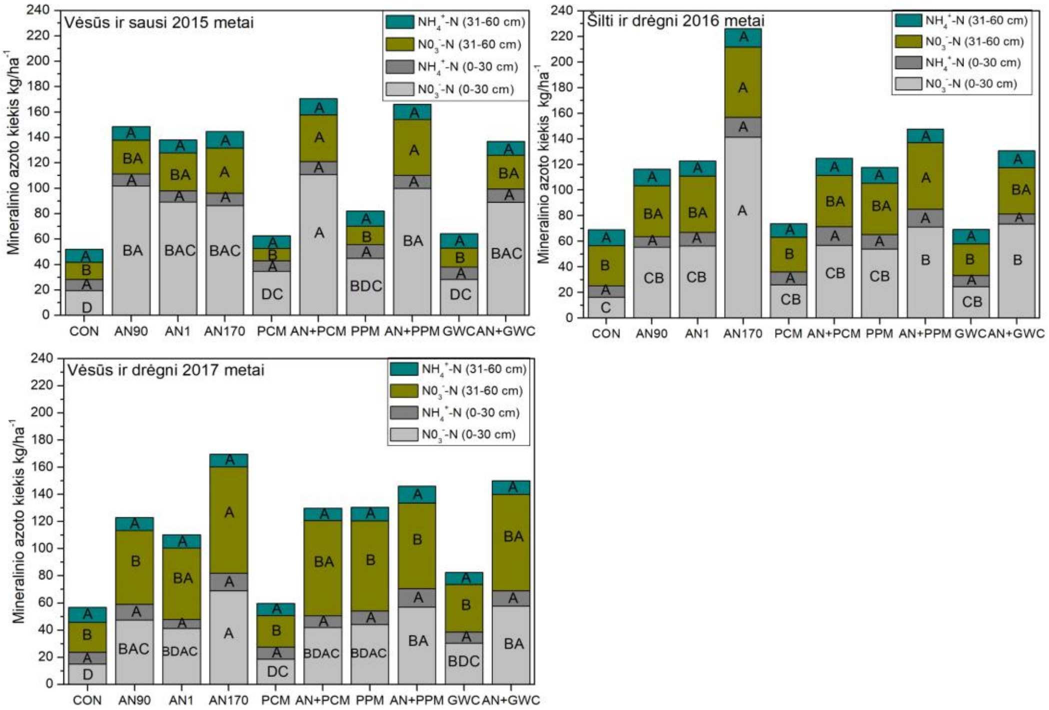
3 paveikslas. Azoto mitybos indeksas (NNI) ir azoto koncentracija kukurūzų žydėjimo metu

Vėsiais ir sausais 2015 metais NNI reikšmės svyravo nuo 0,66 ± 0,03 iki 1,14 ± 0,02, palankesnės kukurūzų auginimo sąlygos 2016 metais turėjo įtakos ir didesnėms NNI reikšmėms, kurios svyravo nuo 0,83 ± 0,02 iki 1,10 ± 0,02. Vėsiais ir drėgnais

2017 metais NNI reikšmės buvo panašios kaip ir 2015 metais ir svyravo nuo 0,71 ± 0,03 iki 1,10 ± 0,02. Kukurūzų mityba azotu AN170, AN + PCM, AN + PPM ir AN + GWC variantuose buvo pakankama ar net perteklinė (NN > 1), o AN90, AN1 ir PPM variantuose – žemiau optimalios (NNI = 0,85–1,03). Nepakankama mityba azotu (NNI = 0,66–0,90) visais metais buvo nustatyta PCM, GWC ir CON variantuose.

Azoto įsisavinimas. Kukurūzų žydėjimo metu azoto įsisavinimas tarp skirtingų variantų ir metų skyrėsi esmingai ($p < 0,01$). Azoto įsisavinimas dėl drėgmės stygiaus 2015 metais buvo žymiai mažesnis nei drėgnais 2016 (7,9–33,4 %) ir 2017 (11,5–39,4 %) metais. Didžiausias azoto įsisavinimas buvo nustatytas AN170 (100,6–113,7 kg ha^{-1} N) ir AN + PPM (85,3–110,9 kg ha^{-1} N) variantuose. Mažiausias azoto įsisavinimas nustatytas GWC (51,3–84,6 kg ha^{-1} N) ir CON (53,9–81,0 kg ha^{-1} N) variantuose. Gauti eksperimentiniai rezultatai patvirtina kitų autorių teiginius, kad trūkstant drėgmės daugelis augalų prasčiau įsisavina azotą (Pandey ir kt., 2000). Reikšmingos įtakos azoto įsisavinimo skirtumams tarp skirtingų metų galėjo turėti ir nevienodas mineralinio azoto kiekis dirvožemyje prieš kukurūzų sėją.

Mineralinio azoto (N_{min}) kiekis dirvožemyje. Mineralinio azoto matavimai parodė reikšmingus skirtumus tarp variantų ($P < 0,05$) dirvožemio viršutiniame (0–30 cm) sluoksnyje, tačiau N_{min} svyravimai gilesniame (31–60 cm) sluoksnyje buvo nereikšmingi (4 paveikslas). Tyrimo metais esminiai skirtumai tarp variantų buvo nustatyti tik nitratinės formos azoto (NO_3^--N). 2015 m. dirvožemio 0–30 cm sluoksnyje N_{min} kiekis svyravo nuo 28,2 iki 111,4 kg ha^{-1}, o variantai mažėjančia tvarka pasidalijo į keturias grupes: AN + PCM ≈ AN + PPM ≈ AN90 > AN170 ≈ AN + GWC ≈ AN1 > PPM > PCM ≈ GWC ≈ CON. Dirvožemio gilesniame sluoksnyje skirtumai buvo mažesni, tačiau variantai išsidėstė beveik tokia pat tvarka kaip ir 0–30 cm gylyje. 2016 m. N_{min} kiekis dirvožemio viršutiniame sluoksnyje svyravo nuo 25,2 kg ha^{-1} (CON) iki 156,8 kg ha^{-1} (AN170), o gilesniame sluoksnyje N_{min} buvo nuo 35,9 kg ha^{-1} iki 69,3 kg ha^{-1}. 2017 m. N_{min} kiekis dirvožemio 0–30 cm sluoksnyje svyravo nuo 23,7 iki 81,8 kg ha^{-1}, o 0–60 cm gylyje gauti rezultatai buvo panašūs ir svyravo nuo 33 iki 87,7 kg ha^{-1}. Kukurūzų žydėjimo metu susidarę N_{min} skirtumai, kurie buvo nustatyti skirtingais metais, iš dalies gali būti paaiškinti tuo, kad pradinis N_{min} kiekis dirvožemyje (0–60 cm gylyje) prieš kukurūzų sėją taip pat gerokai skyrėsi: 2015 m. – 95,6, 2016 m. – 127,4, 2017 m. – 65,7 kg ha^{-1} N. Pažymėtina, kad tyrimo metais dirvožemyje didžioji dalis azoto buvo nitratinės formos (NO_3^--N), o amoniakinės formos (NH_4^+-N) gerokai mažiau.



4 paveikslas. Mineralinio azoto kiekis (kg ha^{-1} N) dirvožemyje kukurūzų žydėjimo metu. Skirtingos raidės parodo esminius skirtumus tarp variantų ($p < 0{,}05$, Tukey's testas)

Apibendrinimas. 2015 metais kukurūzų, auginamų grūdams, vegetacijos periodas nuo sėjos iki žydėjimo buvo vėsus ir sausas, 2016 m. – šiltas ir drėgnas, 2017 m. – vėsus ir drėgnas. Šios kontrastingos aplinkos sąlygos turėjo įtakos ir eksperimento metu matuotiems augalų ir dirvožemio rodiklių pokyčiams. Pagal atliktus biomasės, lapų ploto, chlorofilo indekso (SPAD), azoto mitybos indekso (NNI), azoto koncentracijos, azoto įsisavinimo ir mineralinio azoto (N_{min}) kiekio matavimus galima teigti, kad esminiai skirtumai tarp variantų buvo nustatyti kukurūzų vegetatyvinio periodo pabaigoje, liepos mėnesį, kukurūzų žydėjimo metu. Taigi, galima daryti prielaidą, kad šiuo laikotarpiu atliekami matavimai leidžia gana gerai įvertinti kukurūzų mitybos azotu būklę. Skirtumai tarp variantų 2015 metais išryškėjo šiek tiek anksčiau. Kaip ir buvo tikėtasi, minėti augalų ir dirvožemio rodikliai buvo glaudžiai susiję. Koreliacija tarp SPAD ir NNI buvo 2015 (R^2 – 0,68) ir 2017 (R^2 – 0,69) metais ir šiek tiek mažesnė 2016 metais (R^2 – 0,48). Koreliacija tarp SPAD ir azoto įsisavinimo buvo aukštesnė drėgnais 2016 ir 2017 metais (atitinkamai $R^2 = 0{,}84$ ir 0,74) nei sausais 2015 metais ($R^2 = 0{,}61$). Koreliacija tarp SPAD ir N_{min} kiekio (0–60 cm) buvo aukštesnė 2015 ($R^2 = 0{,}87$) nei 2016 ($R^2 = 0{,}49$) ir 2017 ($R^2 = 0{,}77$) metais. Artima koreliacija buvo gauta tarp NNI ir azoto įsisavinimo (R^2 = 2015 m. – 0,75, 2016 m. – 0,58, 2017 m. – 0,87), taip pat tarp NNI ir N_{min} (R^2 = 2015 m. – 0,73, 2016 m. – 0,61, 2017 m. – 0,88) ir N_{min} ir azoto įsisavinimo (R^2 = 2015 m. – 0,48, 2016 m. – 0,64, 2017 m. – 0,89).

Pagal 2015–2017 metais apskaičiuotas NNI reikšmes galima teigti, kad kukurūzų mityba azotu AN170, AN + PCM, AN + PPM ir AN + GWC variantuose buvo pakankama ar net perteklinė (NNI > 1). Kukurūzų mityba AN90, AN1 ir PPM variantuose buvo mažesnė nei optimali (NNI 0,85–1,03), o PCM, GWC ir CON variantuose nustatyta nepakankama mityba (NNI = 0,66–0,90). Atlikti azoto įsisavinimo ir SPAD matavimai atskleidė panašų variantų eiliškumą, kaip ir NNI. Kukurūzų mityba laukeliuose, kurie buvo tręšti organinių ir mineralinių trąšų deriniu, buvo pakankama, o N_{min} kiekis dirvožemyje (0–60 cm) pastebimai didesnis (ypač 2015 m.) nei laukeliuose, kurie buvo patręšti tik organinėmis trąšomis.

Skirtingų trąšų poveikis kukurūzų mitybos būklei biomasės ir grūdų formavimuisi reprodukcinio periodo metu

Reprodukcinio periodo metu kukurūzai perskirsto maisto medžiagas iš vegetatyvinių organų, tai yra lapų ir stiebų, į grūdus. Iki šios stadijos pradžios vegetatyviniai organai pilnai išsivysto ir nebeauga, tačiau sparčiai auga grūdai. Šiuo augimo laikotarpiu bet koks stresas, ypač vandens trūkumas, gali reikšmingai sumažinti grūdų derlių.

Kukurūzų augimo periodas nuo žydėjimo iki fiziologinės brandos

Biomasė. Kukurūzų pieninės brandos (R3) tarpsniu vidutinė eksperimento biomasė buvo: 2015 m. – 10,88 t ha^{-1}, 2016 m. – 11,63 t ha^{-1}, 2017 m. – 10,05 t ha^{-1}. Tyrimo laikotarpiu granuliuotas paukščių mėšlas esmingai didino biomasės kiekį (24,7 %, arba 2,16 t ha^{-1}), palyginus su netręštu variantu. Granuliuoto galvijų mėšlo įtaka buvo esmingai mažesnė (11,2 %, arba 0,95 t ha^{-1}), o žaliųjų atliekų komposto – nereikšminga. Panaudojus organinių ir mineralinių trąšų derinį biomasė padidėjo maždaug 26,7 %, palyginus su kontroliniu variantu.

Lapų ploto indeksas (LAI). Kukurūzų pieninės brandos (R3) tarpsniu LAI skirtumai tarp variantų buvo reikšmingi: didžiausias nustatytas AN170 (2,48), mažiausias – CON variante (2,06). Pažymėtina, kad nuo tada, kai kukurūzai pasiekė reprodukcinį periodą, LAI pradėjo nuosekliai mažėti.

Chlorofilo indeksas (SPAD). 2015 ir 2017 metais reprodukcinio periodo metu SPAD reikšmės nuosekliai mažėjo, tačiau itin palankiais 2016 metais tokio akivaizdaus mažėjimo nebuvo. 2015 metais R2 vystymosi tarpsniu SPAD reikšmės buvo mažesnės vidutiniškai 5,9 %, R3 tarpsniu – 16,6 % nei žydėjimo metu. 2017 metais R2 ir R3 tarpsniais SPAD reikšmės buvo mažesnės atitinkamai 1,86 ir 4,3 %. Galima daryti prielaidą, kad šie skirtumai buvo susiję su sumažėjusiu azoto įsisavinimu, ypač 2015 metais. Gauti rezultatai buvo panašūs į kitų autorių; pavyzdžiui, Costa ir kt. (2001) nurodo, kad skirtumai tarp skirtingų tręšimo variantų išryškėjo, kai augalai pradėjo senėti. Nepaisant paminėtų skirtumų, visais metais didesnės SPAD reikšmės buvo gautos AN170, AN + PPM ir AN + GWC variantuose, mažiausios – GWC, PCM ir CON variantuose.

Biomasės ir grūdų derlius. Spalio mėnesį, kai kukurūzai pasiekė fiziologinę brandą (R6 tarpsnį), gautas biomasės derlius 2015 m. svyravo nuo 11,47 iki 14,81 t ha^{-1}, 2016 m. – nuo 13,67 iki 19,04 t ha^{-1}, 2017 m. – nuo 12,58 iki 16,49 t ha^{-1} (2 lentelė). Statistinė trejų metų rezultatų analizė parodė esminius metų ir variantų skirtumus, taip pat ir jų sąveikas ($p < 0,01$). Pagal gautą biomasės derlių variantus galima sugrupuoti taip: AN170 ≈ AN + PCM ≈ AN + PPM ≈ AN + GWC > PPM ≈ AN1 ≈ AN90 > PCM ≈ GWC ≈ CON. Kukurūzų grūdų derlius skirtingais metais varijavo gana reikšmingai: 2015 m. – nuo 5,72 iki 6,86 t ha^{-1}, 2016 m. – nuo 6,94 iki 9,56 t ha^{-1}, 2017 m. – 6,37 iki 7,91 t ha^{-1}. Eksperimento metu gautas grūdų derlius, palyginus su Lietuvos ūkininkų vidutiniais derliais, buvo didesnis 34,5 % (2015 m.), 22,2 % (2016 m.) ir 29,3 % (2017 m.) (Eurostat, 2018). Nepaisant kai kurių išimčių, skirtingų trąšų įtaka grūdų derliui buvo beveik tokia pat kaip ir biomasei. Gautas grūdų derlius variantuose, kuriuose derintos organinės ir mineralinės trąšos, buvo panašus į gautą naudojant tik mineralines trąšas (AN170). Palyginus organines trąšas, didžiausias derlius gautas panaudojus granuliuotą paukščių mėšlą, mažesnis – granuliuotą galvijų mėšlą ir žaliųjų atliekų kompostą.

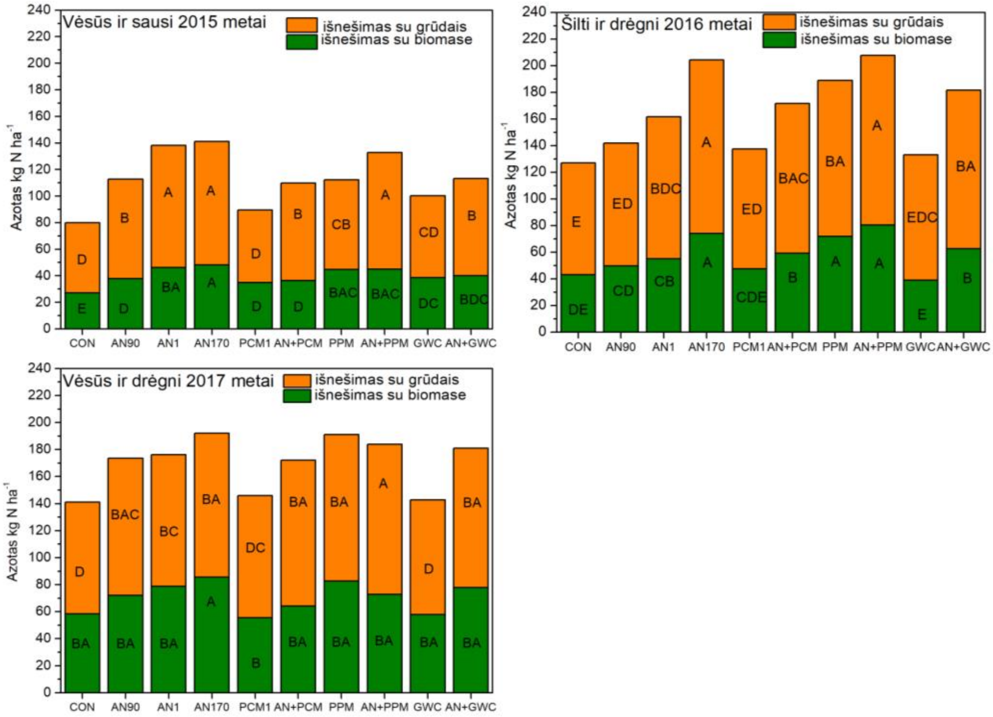
2 lentelė. Biomasės ir grūdų derlius (sausų medžiagų) 2015–2017 metais.

Variantai	Biomasė t ha^{-1}				Grūdų derlius t ha^{-1}			
	2015	2016	2017	vidurkis	2015	2016	2017	vidurkis
CON	11,47 B	13,67 D	12,58 E	12,57	5,72 B	6,94 C	6,37 C	6,34
AN90	13,87 A	16,60 BC	14,64 BDC	15,04	6,70 A	8,41 BAC	7,56 BA	7,56
AN1	14,21 A	17,51 BA	15,31BAC	15,68	6,66 A	8,74 BA	7,50 BA	7,63
AN170	14,53 A	18,52 A	15,49 BAC	16,18	6,85 A	9,02 BA	7,71 A	7,86
PCM	11,76 B	15,27 DC	14,28 EDC	13,77	5,77 B	7,78 BC	7,16 BAC	6,9
AN + PCM	14,30 A	17,60 BA	16,49 A	16,13	6,79 A	8,75 BA	7,88 A	7,81
PPM	13,68 A	17,53 BA	16,26 BA	15,82	6,55 A	8,85 BA	7,91 A	7,77
AN + PPM	14,81 A	17,76 BA	15,72 BAC	16,10	7,11 A	8,94 BA	7,88 A	7,98
GWC	11,62 B	16,20 BC	13,31 ED	13,71	5,72 B	7,82 BC	6,78 BC	6,77
AN + GWC	13,74 A	19,04 A	15,58 BAC	16,12	6,86 A	9,56 A	7,48 BC	7,97
Vidurkis	13,40	16,97	14,97		6,47	8,48	7,42	
Variantai		p < 0,01				p < 0,01		
Metai		p < 0,01				p < 0,01		
Variantų × metų sąveika		p < 0,01				NS (p < 0,19)		

Pastaba. Skirtingos raidės parodo esminius skirtumus tarp variantų ($p < 0,05$, Tukey’s testas).

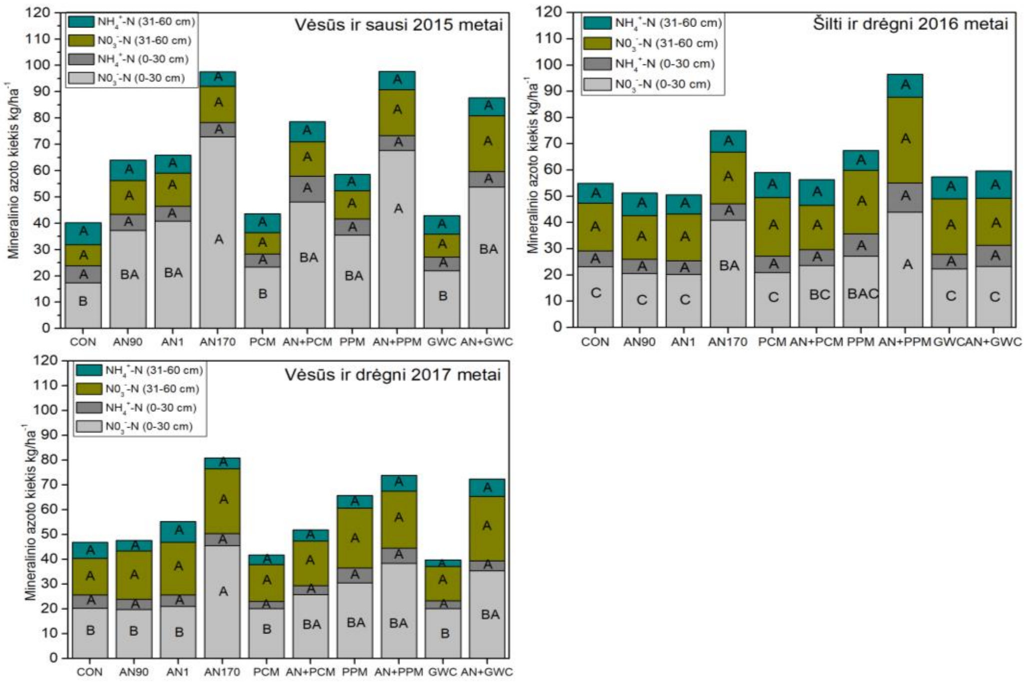
Azoto įsisavinimas. Kukurūzų fiziologinės brandos tarpsniu azoto įsisavinimas tarp variantų skyrėsi esmingai, be to, buvo nustatyta esminga metų ir šių veiksnių sąveika ($p < 0,01$). Azoto įsisavinimas buvo esmingai mažesnis 2015 nei 2016 ir 2017 metais (5 paveikslas). Sėjos–žydėjimo laikotarpiu kukurūzai 2015 m. įsisavino 66,5 %, 2016 m. – 58,3 %, 2017 m. – 55,1 % azoto. Gauti rezultatai yra panašūs į publikuotus kitų autorių (Girma ir kt., 2010). Didžiausias bendras (grūduose ir likusioje biomasėje) azoto įsisavinimas nustatytas šiuose variantuose: AN170 (141,1–204,4 kg ha^{-1} N) ir AN

+ PPM (132,7–207,8 kg ha^{-1} N), mažiausias – CON (79,9–141,2 kg ha^{-1} N), PCM (89,5–145,9 kg ha^{-1} N) ir GWC (100,2–142,8 kg ha^{-1} N). Santykinai didelės kontroliniame variante gautos azoto įsisavinimo reikšmės sutampa su tyrimų rezultatais kitų mokslininkų, kurie šioje tyrimo vietovėje atliko eksperimentus su žieminiais kviečiais (Lazauskas ir Dabkevičius, 1997). Mokslininkai nustatė, kad netręšiant azoto su žieminių kviečių grūdų derliumi, priklausomai nuo veislės ir fungicidų naudojimo, gali svyruoti nuo 68,0 iki 90,8 kg ha^{-1}. Tačiau šiuos du augalus lyginti gana sudėtinga, nes kukurūzai turi didesnį derliaus potencialą nei kviečiai (Teixeira ir kt., 2014).



5 paveikslas. Azoto įsisavinimas kukurūzų derliaus nuėmimo metu. Skirtingos raidės parodo esminius skirtumus tarp variantų ($p < 0,05$, Tukey's testas)

Mineralinio azoto (N_{min}) kiekis dirvožemyje. Po kukurūzų derliaus nuėmimo tarp variantų dirvožemio viršutiniame sluoksnyje buvo nustatyti esminiai N_{min} skirtumai (6 paveikslas), o gilesniame sluoksnyje skirtumai buvo nežymūs. Dirvožemio 0–60 cm sluoksnyje nitratinis azotas 2015 metais sudarė 69,3 % viso mineralinio azoto kiekio, 2016 ir 2017 m. atitinkamos reikšmės buvo 52,6 ir 55,39 %.



6 paveikslas. Mineralinio azoto kiekis (kg ha^{-1} N) dirvožemyje po derliaus nuėmimo. Skirtingos raidės parodo esminius skirtumus tarp variantų ($p < 0{,}05$, Tukey's testas)

Pažymėtina, kad 2015 metais didžioji dalis nitratinio azoto susikaupė dirvožemio 0–30 cm sluoksnyje – tikėtina, dėl tais metais sumažėjusio azoto įsisavinimo ir riboto jo judėjimo į gilesnius sluoksnius dėl drėgmės stygiaus. Didžiausias N_{min} kiekis buvo nustatytas AN170 ir AN + PPM variantuose, mažiausias – CON, PCM ir GWC variantuose. Mineralinių ir organinių trąšų derinys gerokai padidino N_{min} kiekį dirvožemyje, ypač 2015 metais, palyginus su laukeliais, kuriuose buvo naudotos tik organinės trąšos.

APTARIMAS

Eksperimento laikotarpiu 2016 metais susiklostė kukurūzų augimui palankios aplinkos sąlygos ir, jeigu netrūko azoto (AN170, AN + PCM, AN + PPM ir AN + GWC variantuose), buvo gautas santykinai didelis grūdų derlius – 10,43 t ha^{-1} (15 % grūdų drėgnio). Tai 3,49 t ha^{-1} daugiau nei vidutinis tų metų derlius Lietuvoje. Tačiau kitais metais grūdų derlius buvo gerokai mažesnis, pavyzdžiui, vėsiais ir sausais 2015 metais grūdų derlius buvo 24 %, o vėsiais ir drėgnais 2017 metais – 12 % mažesnis nei šiltais ir drėgnais 2016 metais. Sąlygiškai didelė kukurūzų derliaus variacija tarp tyrimo metų skatina geriau suprasti ją lemiančius veiksnius. Eksperimento laikotarpio derliaus svyravimai, kurie buvo nustatyti skirtingais metais, labiausiai gali būti siejami su aplinkos sąlygomis, temperatūros ir vandens stresais. Gauti rezultatai rodo, kad kukurūzų vegetatyvinio periodo metu dominuojantis veiksnys, lemiantis potencialaus derlingumo sumažėjimą, yra temperatūros stresas. Per visą kukurūzų vegetaciją žema oro temperatūra (žemesnė nei 8° C) grūdų derlių mažino maždaug nuo 14,1 iki 25,2 %.

Dar vienas svarbus veiksnys Lietuvos sąlygomis yra vandens stresas, kuris pasireiškia augalų vystymosi laikotarpiu. Lietuva yra drėgmės pertekliaus zonoje, tai yra 80 % iškritusių kritulių išgaruoja, o likusieji patenka į paviršinius vandenis (Tumas, 2003). Vis dėlto kintančio klimato sąlygomis kritulių pasiskirstymas per sezoną yra nevienodas (Rimkus ir kt., 2011). Akivaizdu, kad ateityje prognozuojamo klimato šiltėjimo atveju bus sunku išvengti sausrų.

Auginimo vieta ir aplinkos sąlygos turi įtakos daugelio augalų derliui. Siekiant įvertinti augalų maisto poreikį ir efektyviai naudoti išteklius, būtina prieš augalų sėją įvertinti, kokį tikslų derlių planuojama gauti (Roberts, 2008). Tačiau remiantis šio tyrimo rezultatais galima teigti, kad Baltijos regione yra gana sudėtinga nustatyti, kokį derlių tikimasi gauti, nes potencialų derlių esmingai mažina temperatūros ir vandens stresai. Dar sudėtingiau nuspėti būsimo auginimo sezono temperatūros ir vandens pokyčius.

Eksperimento rezultatai rodo, kad tyrimo vietovėje amonio nitrato 170 kg ha^{-1} N tręšimo norma buvo pakankama geram kukurūzų augimui ir vystymuisi. Tačiau, žvelgiant iš aplinkosaugos pusės, tokia tręšimo norma gali būti per didelė, nes spalio mėnesį po derliaus nuėmimo dirvožemyje liko santykinai daug nitratinio azoto. Po derliaus nuėmimo didžiausias kiekis nitratinio azoto buvo AN170 ir AN + PPM variantuose, todėl galima teigti, kad juose nitratų išplovimo rizika buvo didesnė nei kituose eksperimento variantuose. Ūkininkai pernelyg dideles azoto tręšimo normas dažnai naudoja kaip garantą, be to, per gausiai tręšiama gali būti ir dėl pervertinto planuojamo derliaus. Pavyzdžiui, Suomijoje atliktas tyrimas parodė, kad pasėlių tręšimo rekomendacijos, pagrįstos ūkininkų lūkesčiais, azoto naudojimo praktikoje gali pridaryti esminių klaidų (Valkama ir kt., 2013).

Šio tyrimo rezultatai parodė, kad naudojant granuliuotą galvijų mėšlą ir žaliųjų atliekų kompostą augalų azoto pasiekiamumas buvo mažesnis nei tręšiant mineralinėmis trąšomis. Tačiau granuliuotas paukščių mėšlas beveik prilygo mineralinėms trąšoms. Pagal augalų ir dirvožemio azoto būklės rodiklius (NNI, SPAD, N_{min}) esminiai skirtumai tarp variantų išryškėjo jau liepos mėnesį, vegetatyvinio periodo pabaigoje. Pažymėtina, kad kukurūzų žydėjimo metu augalų ir dirvožemio azoto būklės rodikliai ne tik kiekybiškai įvertino augalų mitybos būklę, bet ir gerai prognozavo galutinį grūdų derlių, todėl ūkininkai gali naudoti šiuos rodiklius praktikoje. Gauti rezultatai buvo panašūs į kitų autorių rezultatus; pavyzdžiui, Muñoz ir kt. (2008) nurodo, kad galvijų mėšlo įtaka augalų derliui ir azoto įsisavinimui buvo esmingai mažesnė nei paukščių mėšlo. Kaip ir tikėtasi, pagal visus azoto efektyvumo indeksus efektyviausiai jis buvo panaudotas variantuose su mažesne tręšimo norma (N90). Pagal azoto efektyvumo indeksus skirtumai tarp variantų, kuriuose buvo derinamos mineralinės bei organinės trąšos (AN + PPM, AN + PCM, AN + GWC) ir kuriuose naudotos tik mineralinės trąšos (N170), buvo nereikšmingi. Palyginus organines trąšas nustatyta, kad efektyviausias buvo paukščių mėšlas, o jo efektyvumas buvo artimas variantams, kuriuose buvo derinamos trąšos, todėl Lietuvoje auginant kukurūzus granuliuotas paukščių mėšlas gali būti laikomas efektyviu azoto šaltiniu. Tačiau žaliųjų atliekų kompostas ir granuliuotas galvijų mėšlas turėtų būti derinamas su mineralinėmis azoto trąšomis.

Šio eksperimento rezultatai, susiję su mineralinių ir organinių trąšų įtaka kukurūzų augimui, vystymuisi, produktyvumui ir grūdų derliui, buvo panašūs kaip ir kitų mokslininkų tyrimų, tačiau yra keletas aspektų, kurie šiame darbe nebuvo giliau ištirti ir išsamiau aptarti. Nebuvo įvertinti azoto išplovimo į vandenis ir patekimo į orą nuostoliai. Šiuo metu Europos Sąjungoje išlieka aktualus klausimas, kaip, siekiant patenkinti augalų poreikius, efektyviai panaudoti azoto šaltinius. Galioja bendra taisyklė, kad azoto šaltiniai turi būti naudojami tvariai ir tausojant aplinką. Europos Sąjungos direktyva (2016/2284) jos nares įpareigoja mažinti tam tikras (sieros dioksido, azoto oksidų ir kt.) emisijas į orą. Ūkininkai taip pat privalo atsižvelgti į reikalavimus nitratų direktyvos (91/676/EEB), kuri pažeidžiamose zonose riboja mėšlo tręšimo normas (Schröder ir kt., 2013).

Būsimi tyrimai ir studijos yra reikalingi ne tik siekiant įvertinti azoto panaudojimo efektyvumą augalo atžvilgiu, bet ir įvertinti poveikį aplinkai (vandenims, orui). Šio tyrimo metu mėšlo panaudojimas buvo vertinamas tik pirmaisiais metais, tačiau nebuvo tirta potencialiai naudinga ilgalaikė organinių trąšų įtaka. Taip pat nebuvo tirta potenciali sunkiųjų metalų kaupimosi augaluose ir dirvožemiuose rizika, kuri turėtų būti vertinama tręšiant organinėmis trąšomis, ypač žaliųjų atliekų kompostu (Staugaitis ir kt., 2016).

IŠVADOS

1. AquaCrop ir AgroC modeliai gerai simuliavo lauko eksperimentinius duomenis: bendrąją antžeminės dalies biomasę (RMSE = 0,54–1,33 t ha^{-1}, R^2 = 0,97–0,99), grūdų derlių (RMSE = 0,35–1,01 t ha^{-1}, R^2 = 0,92–0,99), lapijos dangą (lapų plotą) (RMSE = 4,01–17,02 %, R^2 = 0,71–0,99) ir dirvožemio drėgmės kiekį (RMSE = 0,012–0,056 cm^3 cm^{-3}, R^2 = 0,41–0,78).

2. Nemoralinėje klimato zonoje, lauko eksperimento vietovėje, AgroC modelis apskaičiavo gana didelį kukurūzų ankstyvos veislės potencialų grūdų derlių – 11,25–11,85 t ha^{-1}, o AquaCrop modelis prognozavo 10,31–10,95 t ha^{-1} derlių.

3. Su AquaCrop modeliu simuliuoti rezultatai parodė, kad 2015 metais grūdų derliaus sumažėjimas dėl žemos temperatūros buvo 2,6 t ha^{-1}, 2016 metais – 1,54 t ha^{-1}, atitinkamai AgroC modelio rezultatai buvo 2,39 ir 1,90 t ha^{-1}. 2015 metais AquaCrop modeliuotas derliaus sumažėjimas dėl drėgmės trūkumo buvo 0,81 t ha^{-1}, 2016 metais – 0,48 t ha^{-1}. AgroC modelio simuliuotas derliaus sumažėjimas buvo didesnis: 2015 metais – 1,93 t ha^{-1}, 2016 metais – 0,94 t ha^{-1}.

4. Tręšiant granuliuotu paukščių mėšlu (N170 kg), grūdų derlius beveik prilygo gautam panaudojus amonio nitratą. Granuliuotas galvijų mėšlas ir žaliųjų atliekų kompostas lėmė gana mažą grūdų derliaus priedą. Dalį amonio nitrato (N80) pakeitus organinėmis trąšomis, derlius reikšmingai nesumažėjo ir buvo panašus, kaip ir tręšiant vien mineralinėmis trąšomis (AN170).

5. Kukurūzų žydėjimo metu apskaičiuotas azoto mitybos indeksas variantus leido sugrupuoti pagal mitybos būklę. Amonio nitratas ir jo deriniai su organinėmis trąšomis (N170 kg) užtikrino pakankamą ar net perteklinę mitybą azotu (NNI > 1). Sąlygiškai geras mitybos lygis pasiektas tręšiant granuliuotų paukščių mėšlu (NN1 0,85–0,99), tačiau panaudojus granuliuotą galvijų mėšlą ir žaliųjų atliekų kompostą kukurūzų mityba azotu buvo nepakankama (NNI 0,78–0,90).

6. Dirvožemio mineralinio azoto (N_{min}) kiekio ir azoto mitybos indekso matavimai, atlikti žydėjimo metu, variantus leido sugrupuoti pagal tokį pat eiliškumą. Šis variantų eiliškumas buvo toks pat, kaip ir galutinis grūdų derlius, todėl šie mitybos indikatoriai gali būti naudojami vertinant kukurūzų mitybos N būklę ir prognozuojant grūdų derlių.

7. Kukurūzus auginant grūdams, prieš sėją kaip pagrindinis azoto šaltinis gali būti naudojamas granuliuotas paukščių mėšlas, o granuliuotas galvijų mėšlas ir žaliųjų atliekų kompostas turėtų būti naudojami kartu su mineralinėmis trąšomis.

8. Didžiausias grūdų derlius gautas kukurūzus patręšus amonio nitratu arba granuliuotu paukščių mėšlu (N170 kg), tačiau toks tręšimas padidino mineralinio azoto kiekį dirvožemyje po derliaus nuėmimo, o tai rodo galimai didesnę nitratų išplovimo riziką.

PASKELBTŲ PUBLIKACIJŲ SĄRAŠAS

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THE EFFECTS OF ORGANIC AND MINERAL FERTILISERS ON MAIZE N STATUS UNDER WATER AND COLD STRESS CONDITIONS IN A NEMORAL CLIMATE

DOCTORAL DISSERTATION

INTRODUCTION

Problem statement

Maize (*Zea mays* L.), one of the three most cultivate crops in the world, is an important source of food, feed, fuel and fibre (Tenaillon and Charcosset 2011). In the European Union (EU-28), grain maize production accounts for 20.8% of the total cereal production (FAOSTAT 2016), and until 2026, a further expansion of the maize cultivation area of around 8% is expected. Maize cultivation with probably increase because of the stronger growth of this species compared with other cereal plants, and the potential to further increase maize yields is relatively high, especially in the new countries of the European Union (EU-N13), taking into account the high maize yield gaps compared to the EU-15 (EU Commission 2016). In 2002, grain maize has been cultivated in Lithuania on an area of 2,900 ha^{-1}, and during the last 5 years, the cultivation area has significantly increased from 9,930 to 19,000 ha^{-1} (FAOSTAT 2017). On a global level, maize grain production has substantially increased since the development of hybrid maize in the late 1930s, and yield levels quintupled due to the combination of genetic improvements and changes in agronomic practices (Tollenaar and Lee 2011). However, in areas at high latitudes, characterised by short vegetation periods and low temperatures, maize cultivation is challenging, although the development of short-cycle varieties has facilitated maize cultivation under low temperatures (Riva-Roveda et al. 2016), and the extension of maize cultivation has been accompanied by a dramatic adaptation of this plant to unfamiliar environmental conditions.

In the Nordic-Baltic countries, successful maize forage production is possible at a latitude of at least 58°N; however, currently, only a minor proportion of maize is harvested as grain in Denmark, Lithuania and Sweden (Swensson 2014). Despite the rapid maize expansion in northern Europe, the short growing seasons, the occurrence of late/early frosts, the rain quantity, which usually does not match with the highest water demand during the growing period, and the incidence of drought are considered to be the primary factors still limiting maize expansion in northern regions (Olesen et al. 2011). The experimental separation of the effects of temperature and water stress on plant growth is cost- and labour-intense; however, crop models, which are used more frequently these days, are available for many crops such as maize, and if calibration and validation data are available, crop models represent a tool to capture spatial and temporal variations in crop development, growth and yield in reaction to temperature and water stress. Despite the fact that maize areas are still expanding and crop models are readily available, which may offer solutions to many significant issues, in northern regions, not much is known about grain maize growth and potential yields under changing climatic conditions. In this sense, novel research strategies are required to answer the significant questions asked by farmers, practitioners and governmental organisations.

Although the scientific basics for maize mineral nutrition has been established several decades ago, most maize yield formation and nutrition experiments have been carried out in traditional maize breeding zones under favourable environmental conditions. However, in marginal cultivation regions such as Lithuania, the synchronisation of nitrogen supply from organic fertilisers with maize crop demand still poses a significant problem, and the impacts of the application of organic fertilisers prior of maize sowing have only been investigated fragmentally. Another problem is that research of the efficiency of organic fertilisers is focused on long-term effects of copious fertilisation, whereas less attention is drawn to the efficiency of single applications of organic fertilisers, especially pelletised fertilisers. Although plants do not differentiate the nutrients supplied through organic or inorganic sources, an important issue is that of nutrient availability, mainly in sufficient quantity, in appropriate forms and at the growth stage when nutrient availability is critical for optimum growth and yields (Pretty et al. 2010).

A large number of recent studies focused on specific issues such as various aspects of fertilisation with organic fertilisers or their combinations (Riedell 2014). However, there is still a lack of such experiments in northern Europe, where specific reactions may occur and affect regular nutritional indicators of maize when grown under low temperatures and periodical water stress conditions. Currently, a wide range of various diagnostic nutrition indicators are available, which, in a certain plant growth stage, can non-destructively or destructively evaluate the nutritional state. Such indicators can also potentially estimate the risk of leaching into surface waters, which is particularly relevant in the Baltic area, where the excess of nitrogen and phosphorus is predominant in the majority of rivers and lakes. In Lithuania, silage maize has been grown for more than 70 years (Lazauskas 1987), and previous studies were mainly orientated towards certain questions relevant to that period, such as the determination of the proper crop density or various fertilisation issues (Jakštaitė et al. 1982). However, when growing modern grain maize varieties under a cool climate, the focus is rather on grain needs to re-evaluate the use of organic fertilisers for this crop.

Hypothesis

This thesis tested the following hypotheses:

1. The combination of field experiments and modelling approaches enables to quantify maize yield potential and yield gaps resulting from abiotic stress under a nemoral climate.

2. Sufficient N nutrition can be secured with ammonium nitrate alone or in combination with organic fertilisers, while nitrogen nutrition index and soil mineral content analyses can reliably indicate plant N status for monitoring purposes.

The main aims of this study were to disentangle and quantify the impacts of temperature and water stress on maize yield, to evaluate the effects of different fertilisers on yield formation and to propose tools for monitoring the grain maize N nutrition status.

Objectives of this study

1. To assess the suitability of AquaCrop and AgroC models to simulate maize growth and development and to estimate site-specific yield potentials.
2. To identify and quantify the occurrence of yield gaps as a result of abiotic stress.
3. To investigate the impacts of different organic fertilisers used solely or in combination with ammonium nitrate on maize biomass accumulation and grain yield.
4. To evaluate the feasibility of plant and soil N indicators of maize cultivated with different fertilisers.
5. To estimate the nitrogen efficiencies of different fertilisers and to evaluate their effects on mineral soil N after the harvest.

Defended statements

1. AquaCrop and AgroC models provide suitable experimental data of major traits of grain maize in the nemoral zone under non-limited N supply.
2. Water stress, which is of secondary importance after temperature under a nemoral climate, occurs periodically and results in significant maize grain yield losses.
3. Mid-season plant and soil N indicators can be used to adequately assess the contribution of fertilisers of different origin to maize grain productivity and soil N supply.
4. Sufficient N supply for maize can be secured with the application of 170 kg ha^{-1} of N as ammonium nitrate, poultry manure, or as combination of ammonium nitrate and cattle manure or green waste compost.

Originality of the research work

The novelty of approach includes combination of two different methods: field experiments and modelling were used to study maize growth peculiarities under conditions of nemoral climate. The specific aspect of this study was the quantification of maize yield potential and the separation of water and temperature stress on maize growth and development with two models of different complexity. It has been proven that low temperature occurring during the maize vegetation, is the dominant factor for the potential yield losses, while the impact of water stress is of secondary importance.

In addition, the efficiencies of different pelletised organic fertilisers and green waste compost as well as their combination with mineral fertilisers were assessed. For the first time in this region, nitrogen nutrition index and soil mineral content analyses were validated and have been confirmed as reliable indicator of maize N nutrition status.

Practical importance of the research work

The contribution of this study refers to the investigation of the main abiotic factors limiting potential grain maize yield under local climatic conditions, identified with the AquaCrop and AgroC models. The results of this study will provide a scientific basis for the optimisation of maize management strategies.

The experimental results will contribute to adjustment of N nutrition to grain maize requirements under nemoral climate conditions. In particularly, when organic sources of N such as pelleted manures or green waste compost are used. Nitrogen status indicators and handy tools, such as SPAD, were successfully employed in this study for maize N status monitoring and thus can be recommended for the wider use in farming operations in this region.

Approval of the dissertation

Based on this dissertation, two publications have been published in Journals with a citation index (Impact Factor) in the *Clarivate Analytics Web of Science* database. The research results were presented on five international conferences.

Volume and structure of the dissertation

The doctoral thesis is written in English. It consists of 123 pages, 23 tables and 19 figures. A total of 187 reference sources are cited in the dissertation. The dissertation contains the sections Abbreviations, Summary, Introduction, Literature Review, Material and Methods, Results and Discussion, Conclusions, References, and List of Publications.

1. LITERATURE REVIEW

1.1. Maize cultivation in a global context

Maize (*Zea mays* L.), also known as corn, is a plant which belongs to the grass tribe Maydeae of the family Poaceae (Gramineae), commonly known as grass family. Maize is a C4 plant and has a specialised physiology with Kranz anatomy (special leaf structure), which makes it well suited to hot and dry climates, although extensive breeding interventions have made this crop appropriate for cold regions (Chaudhary et al. 2014). Maize is grown from 58°N to 40°S, from below the sea level to elevations higher than 3,000 m and in areas with 250 mm to more than 5,000 mm of rainfall per year (Dowswell et al. 1996). From its origin in Mexico, maize has spread throughout the world and now has the largest annual production among cereal crops (Edmeades et al. 2017). According to the first historical record, maize was introduced to Europe, Spain, from the Caribbean by Colombus in 1493 (Tenaillon and Charcosset 2011). Since then, maize cultivation areas have slightly expanded, the highest increase of maize production is related to the appearance of hybrid maize at the beginning of the 20th century. Increasing grain yields are associated with changes in agronomic practices (irrigation, fertilisation, tillage practices, plant spacing, planting date, etc.) and with genetic improvements (transgenic technologies, canopy photosynthesis, kernel number) (Tollenaar and Lee 2011). At present, ~75% of the global maize yield are produced in regions with a warm climate, mainly the American Midwest, Central Mexico, Southern Brazil, the maize belts of Argentina and China, parts of Europe, South Africa, and some areas of India and Indonesia (Ray et al. 2015). Maize is one of the most important crops in Europe and is produced on nearly 18 million hectares, accounting for 71.4% of the agricultural area in eastern Europe and for 16.3% and 12.2% in southern and western Europe, respectively, but only for 0.1% in northern Europe (FAOSTAT 2016). The EU Commission’s forecast for 2014–2024 (EU Commission 2014) suggests that over the next decade, the production of maize and wheat will increase at the expense of other cereals. In the last two decades, the rapid development of maize cultivation has been noticed in northern Europe. From 1992–2016, the maize harvest area in northern Europe increased by 2.4 times, with a production increase by 12.3 times (FAOSTAT 2016). Generally, maize production is still expanding due to an increasing market and an increasing interest in maize in non-food sectors (e.g., bioenergy production). Therefore, it is predicted that by 2050, the maize demand will double in the rapidly developing world, with significant price increases (Rosegrant et al. 2009).

1.2. The impacts of climate change on maize production

On a global level, much has been done to achieve high crop yields, but the question how to balance the high productivity of crops with fertilisation and water supply under changing climatic conditions is becoming more and more relevant. In many countries, agriculture is seriously threatened by the prospect of a changing climate with more frequent droughts, flooding, and harvest losses. Although it is expected that in the near future, climate change will cause crop yield losses in some regions, in other regions, such as northern Europe, the present northern limit may expand further north as a result of climate change and the development of short-season hybrids. These expected climatic changes may be beneficial to plants such as maize. In general, maize yields are still increasing in most areas worldwide, with the most rapid yield increases in Portugal, France and Eastern Europe as well as in the Corn Belt region of the USA (Ray et al. 2012). Data from several studies also confirm the general assumption that maize cultivation conditions at northern latitudes will improve due to climatic changes, mostly because of changing temperatures and global radiation. According to Elsgaard et al. (2012), by 2040, the cropping share of maize in southern Scandinavia and the Baltic countries may increase by 4–20%, while in other northern countries such as Finland and Estonia; maize area may increase by 10%. Supit et al. (2010) suggests that in the near future, the maize yield potential will increase in the majority of the European countries. For instance, the forecasted annual increases are 0.12 t ha^{-1} in Germany, 0.11 t ha^{-1} in Lithuania, 0.09 t ha^{-1} in Poland and the United Kingdom, while in other countries with some of the largest maize areas, potential losses are expected: −0.09 t ha^{-1} y^{-1} for France and Italy, −0.08 t ha^{-1} y^{-1} for Bulgaria and −0.07 t ha^{-1} y^{-1} for Spain and Greece. When comparing different European regions, it is predicted that by the end of the 21st century, temperatures in Europe will mostly increase in the northern regions, mainly in winter (December–February) and spring (March–May) (Ruosteenoja et al. 2007). In comparison with the period 1961–1990, it is forecasted that according to different scenarios, by the year 2100, mean air temperature in northern Europe will increase from 4.5–7.5°C in spring. This rise in temperature in northern Europe is predicted to be about 2°C higher than that in the East, South or West of Europe. It is expected that due to the rising temperatures in northern Europe, the rather short growing seasons will become significantly longer, and the predicted sowing date of some plants will be up to 41 days earlier compared to today (Rötter 2014). Researchers have stated that temperature and solar radiation limit the yield of grain maize not only in northern Europe, but also in other regions. For example, Ceglar et al. (2016) analysed the intra-seasonal and inter-annual variation in grain maize yields and identified temperature and solar radiation as the main meteorological drivers of crucial spatial differences influencing grain maize yield over southern, eastern and northern France. Although maize phenology strongly depends on air temperature and solar radiation, these factors alone do not accurately determine the point when the plant reaches different development stages. In practice, the term “sum of growing degree days” (GDD) is often used to determine maize development and growth stages. Principally, GDD values are being summed over a specific period of time, and the received values can be used to forecast crop development. There is a large volume of published studies describing the relationship between GDD and cop development (Craufurd et al. 1998, Bartholomew and Williams 2005). At higher latitudes, due to limited heat resources required for grain maize maturity, short-vegetation varieties are usually preferred.

Changed precipitation patterns against the background of a changing climate suggest that rainfall and, consequently, available water content for maize production will be reduced in many parts of the world, mainly in warm climate zones such as northern Brazil as well as North and South Africa (Fraser et al. 2013). On the other hand, the predicted climate change will bring more precipitation to northern Europe compared to southern Europe (Rötter et al. 2013). A warming climate increases the opportunities and relevance of maize expansion in marginal areas such as Lithuania; however, as a consequence of climate change, more frequent and longer drought periods are expected in the future. Drought occurs with greater periodicity within the interior rather than exterior of continental Europe, but it can also occur in high-precipitation areas, with a significant negative impact on agricultural production (Lloyd-Hughes and Saunders 2002). Rey et al. (2016) showed the significance of supplemental irrigation in the UK to reach yield and quality assurance and, thereby, guarantee profitable crop production in dry seasons, regardless of the fact that many crops grown in the UK are rainfed. Xiong et al. (2010) investigated the significant spatial differences in drought impacts at the river basin and provincial level and suggested that in broad terms, water availability for agriculture declines in southern China, but remains steady in northern China. Holzkämper et al. (2015) pointed out that future grain maize production in Switzerland can benefit from reduced radiation deficits and reduced growth temperature limitations; however, to minimise the unwanted effects of climate change, adaptation efforts would tackle increasing heat and drought stress and yield losses through accelerated development. Environmental conditions considerably influence maize growth, and Ray et al. (2015) stated that for the last three decades, growing season temperatures and precipitation explained ~22% (~0.9 tons ha^{-1} year^{-1}) or more of year-to-year variations in global average maize yield. Moreover, yield variations are mostly greater in areas of lower yields.

1.3. Maize cultivation in the cool climate of the Nordic-Baltic region

Currently, the grain maize growing conditions in high latitudes can be described as rather unfavourable. Besides, in regions such as northern Europe, maize has a small number of effective growing days, i.e. the number of days when temperature is non-limiting. However, current projected climate scenarios demonstrate a shift in maize development northwards, and the previously mentioned expected changes might open the door to new plants and encourage the production of grain maize, which is not traditionally grown in this region. By the end of this century, maize could become a new plant to be grown in favourable growing regions at latitudes > 60°N (Peltonen-Sainio et al. 2008). Nevertheless, currently, further research is necessary, including field experiments and modelling studies to increase our understanding of the interactions between environmental, genetic and management factors and the consequent impacts on the performance of grain maize in regions at high latitudes (Mussadiq et al. 2012).

In northern Europe, due to the specific climatic conditions, maize was mainly grown for silage; however, the emergence of new varieties, combined with climate change and the growing demand for grain maize, has encouraged the expansion of grain maize cultivation outside the traditional zones, such as in regions of cooler climate (Soane et al. 2012, Spiertz 2014). Modelling studies predict a further development of maize to northern regions in the coming decades (Chung et al. 2014). Nonetheless, the extent of crop development to northern regions will depend on the development of agro-technological and plant breeding techniques (Ewert et al. 2005). Although it is expected that maize cultivation will further expand, currently, varieties adapted to the local climate are not bred in northern countries such as Sweden or Lithuania (Mussadiq 2012); thus, farmers choose to grow only hybrids developed for international use, which are not always suited for a specific northern region.

In the Nordic-Baltic countries, successful maize forage production is possible to at least 58°N, and only a minor proportion of maize is harvested as grain maize in Denmark, Lithuania and Sweden (Swensson 2014). Although in the above-mentioned countries, maize areas comprise rather a small part in comparison to other crops, the maize cultivation area is constantly increasing. For instance, in Lithuania, over the past two decades, the maize harvest area almost doubled (FAOSTAT 2016).

The main limitations of maize cultivation for grain production in northern Europe are the short growing seasons, early and late frosts and the variability of precipitation at sowing and harvesting, as well as the occurrence of drought within the vegetation period (Olesen et al. 2011). Due to many of the factors that are presently limiting maize growth and development, it is extremely important to select the appropriate maize variety to ensure high yields. According to a well-known and widely used FAO rating system, maize varieties are divided into nine different classes (Zscheischler et al. 1990). In the FAO classification, the classes of maize varieties, according to the length of their vegetation period, are short, long-period or intermediate. In northern Europe, short-season varieties with an FAO number between 180 and 230 are usually selected for grain maize, as those varieties require a lower sum of temperature to reach physiological maturity and have a relatively high yield. However, it is rather difficult to select an appropriate maize variety. The list of varieties available on the market is rather large, although there is a lack of fields experiments which would contribute to revealing the most adequate variety. In this study, according to the recommendations of a local expert, a short-season grain maize variety (characterized as FAO 190) was used.

In Nordic-Baltic countries such as Latvia and Lithuania, maize for forage was first cultivated in the 1960s (Gaile 2009, Lazauskas 1987). During that period, relatively simple, but important studies were carried out to determine the most appropriate fertilisation rate and the impacts of organic fertilisers on maize yield and quality as well as to select the most adequate sowing date and the type of soil tillage.

The majority of those comprehensive studies, related to different maize growing techniques for silage management aspects, were carried out before 1980. Up to now, previous studies highlighted some impacts of climate change and different nitrogen levels on maize productivity (Povilaitis et al. 2013). For example, Gaile (2012) addressed the impact of different sowing dates on maize yield and quality. A detailed study by Danish researchers (Ozturk et al. 2018) suggested that due to climate change, the current maize management practices will have to change in the future, such as levels of N inputs, and NO_3^--N leaching to surface waters will significantly increase. From a historical point of view, when growing maize for forage, many copious and comprehensive studies have been carried out in northern Europe, but little concern is still given to maize in order to receive high grain yields. At present, in northern Europe, little is known about the impacts of low temperatures and water stress on grain maize productivity as well as about potential yields and adaptation to climate change. More research is therefore needed to provide data for policy makers, governmental agencies and farmers.

1.4. Maize growth modelling

In sections 1.2 and 1.3, I showed that in the near future, various stresses such as heat and drought are being predicted in different regions and will suppress plant yields, and crop models may represent these effects that adversely affect plant growth and development (Jin et al. 2016). The first classical model of canopy photosynthesis, which was based on the light attenuation within a crop and the light response of leaf photosynthesis, was developed by Monsi and Saeki (1953) in Japan. This publication, which is still the source of inspiration for agronomists, ecologists and botanists, ushered in a new research area on crop structure and functions. Since then, the growing knowledge of the processes related to the growth and development of plants as well as the emergence and availability of computers has been affecting the popularity of plant models. Traditionally, such a model is characterised as a mathematical equation describing a physical system, e.g., the soil–plant–atmosphere, and simulates the behaviour of a real crop by predicting the growth and development (Jame and Cutforth 1996). In other words, plant modelling, which combines many disciplines and provides additional knowledge of how the crops respond to environmental and agronomic management practices, helps to identify critical-limiting factors and yield potential gaps (Penning de Vries et al. 1989). Crop models are commonly used for three major goals: for research, for decision-making (management strategies) and for education. The scales (levels) at which crops models are used vary considerably. Generally, the following scales are distinguished: global – national – regional – agro-ecological zone – farm – field (Jones et al. 2017). Nowadays, researchers offer numerous crop models with different complexities, and such a wide selection of models provides a possibility to choose the best model depending on the research goal. Crop growth models can be roughly divided into three different types: mechanistic, hybrid and empirical models

(Di Paola et al. 2015). Empirical models are rather simple and based on one or more statistical dependencies between environmental factors and final production (biomass, grain yield). Besides, those models do not require many input parameters. There are numerous models of this type, such as GLYCIM (Reddy et al. 1995), FARMSIM (van Wijk et al. 2009), LUPINMOD (Fernández et al. 1996), SIMRIW (Horie et al. 1995), STICS (Brisson et al. 2008). Mechanistic models are more orientated toward one or more specific system components, e.g., nutrients, water, and require a higher number of input parameters than empirical models; they are widely used and include the models CropSyst (Stöckle et al. 2003), DayCent (Necpálová et al. 2015), JULES-crop (Osborne et al. 2015), RICEMOD (McMennamy and O'Toole 1983), RZWQM2 (Xi et al. 2017). Hybrid models can be characterised as a mix of empirical and mechanistic approaches (Spitters and Schapendonk 1990). Prominent examples are CERES-4.0 (Jones et al. 2003), Daisy (Abrahamsen and Hansen 2000), EPIC (Sharpley and Williams 1990), PEGASUS (Deryng et al. 2014), WOFOST (Supit et al. 1994). To achieve adequate simulated results, irrespective of the purpose for which the models are used, a principle rule is that they have to be calibrated and later validated under local conditions (El-Sharkawy 2011). Those procedures are necessary, especially when modelling crop growth in a non-traditional growth area, e.g., maize growth in cold climates. The weaknesses of conventional experience-based agronomic research (field experiments) are that crop production functions were derived from statistical analysis without referring to the underlying biological and physical principles involved (Jame and Cutforth 1996). In contrast, crop models, which combine disciplines such as agro–meteorology, plant physiology, soil science and agronomy, allow a deeper insight into the processes that are difficult to be analysed with the use of traditional data from field experiments. However, to obtain the most precise results, two different approaches (field experiment and modelling) should be combined, i.e. complement each other. Thus, crop models have to be calibrated and validated under specific site conditions. Over the past decades, many teams around the world have developed a variety of models for modelling processes in the system soil–water–plant; however, the focus was mainly put on one element of the system (Negm et al. 2014). Many models for simulating different biochemical cycles have been designed for maize as one of the most important plants in the world. Some of these models are rather complex and can simulate processes related to plant interactions with nitrogen, phosphorous, potassium, water and soil organic carbon. Such models are usually hybrid or mechanistic, for instance APES (Donatelli et al. 2007), DSSAT (Jones et al. 2003), SALUS (Pezzuolo et al. 2014). Other models, such as AgroMetShell (Mukhala and Hoefsloot 2004) or MCWLA (Tao et al. 2009), analyse only specific areas such as yield response to water. Recently, crop models have been used as a tool for measuring the impact of predicted climate change on plant productivity (Senthilkumar et al. 2015). In many cases, the effect of climate change on plants is a debatable issue, and Islam et al. (2012) raised the question whether measures such as fertilisation or adequate sowing time will be used in the future in the same way as they are used now. More and more frequently, models are used as a means to know the effect of the application of one or another plant-growing system in a long-term perspective. Although crop models are an effective tool complementing the knowledge acquired in field experiments, models should be periodically updated and supplemented with new information, reflecting findings in agronomy, plant physiology, soil science and other disciplines (Rötter et al. 2012). It is believed that plant models will become more popular and will be widely used in the near future. In this respect, AquaCrop is a prominent example. Since the release of AquaCrop in January 2009, it has been periodically developed. In August 2012, version 4.0, and in October 2015, version 5.0 was released, and the current version 6.0 was released in March 2017 (Vanuytrecht et al. 2014, Foster et al. 2017). Besides, this model, which simulates the yield response of different herbaceous crops (including maize) to water, has widely been used under different environmental conditions (Abedinpour et al. 2012, Ran et al. 2018). In comparison to the AquaCrop, which is friendly for users and is classified as an empirical model, mechanistic models such as AgroC (Klosterhalfen et al. 2017) are more complex, but rather flexible, which means that all plant, soil and water parameters are accessible and can be modified. This allows to increase the spatial application range and to analyse a broader range of environmental conditions.

In this thesis, two different complexity models, AquaCrop and AgroC, were selected in order to meet the set objectives concerning the effects of cold and water stresses on maize growth and development. The AquaCrop model was selected because it does not require a large number of input parameters in comparison to other models and is periodically updated; it can therefore easily be adapted to different environmental conditions. The main characteristic of the AgroC model is that all parameters of plant development and growth are available and can be modified if required. The comprehensive field experiments carried out within the scope of this PhD thesis allowed to evaluate both models.

1.5. Yield potential and yield gaps of maize

The demand for food will increase significantly in the near future. It is estimated that until 2050, due to a rapidly growing population, the total global agricultural production will have to be increased by 60% (Alexandratos and Bruinsma 2012). Concerns about food security and rising grain prices have led to the global increase of research related to crop yield gaps. In this situation, the notion of potential yield and yield gaps becomes useful in solving the previously mentioned problems. The concept of yield potential is defined as the yield of a crop variety when grown without abiotic (e.g., water, nutrients) and biotic stresses and with optimal agronomic management (Evans 1993). The yield gap is characterised as the difference between yield potential and actual yield (Lobell et al. 2009); this concept is illustrated in Figure 1. In this PhD thesis, the emphasis was put on the following factors affecting maize growth and development: temperature, water and nitrogen, which are the most limiting factors affecting maize expansion in the Nordic-Baltic region.

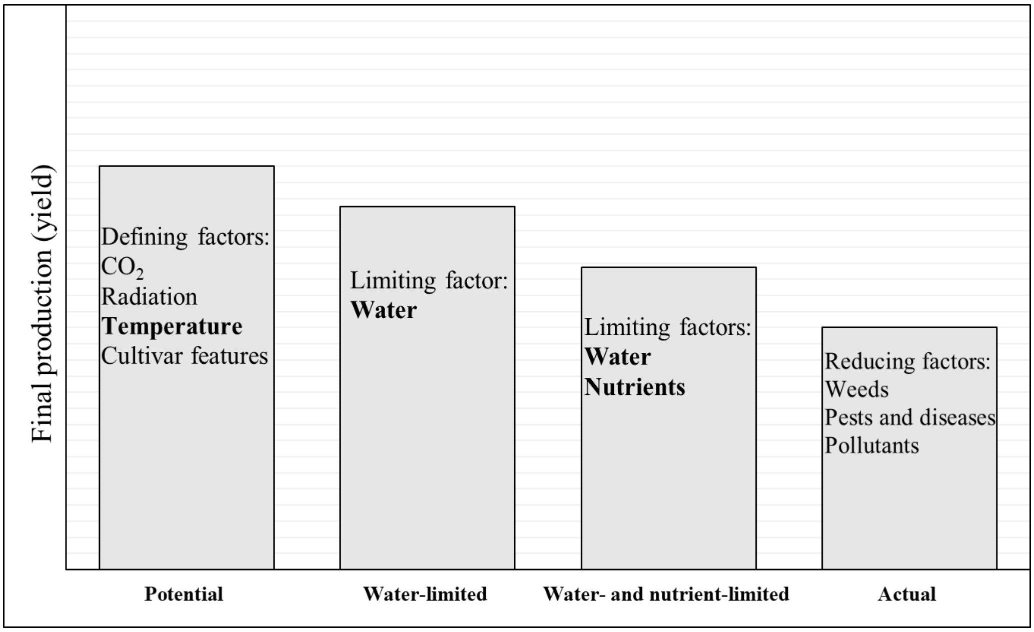

Figure 1. Different levels of crop production and limitation of the yield gaps (modified from van Ittersum et al., 2013). Bold factors (temperature, water, nutrients) mean that they were evaluated in this study.

In the last decade, the amount of publications related to yield gap analysis has increased rapidly. In those analyses, potential yields were determined for different plants and in different scales, including global, regional and farm (local) levels (Liu et al. 2017). Traditionally, there are several methods to determine potential yield: by using model simulation, by carrying out field experiments and by preparing yield contests. Also, an alternative, albeit less popular way to determine maximum yield can be to use the yields provided by the farmers (Lobell et al. 2009). All these listed methods have various advantages and disadvantages, and it is obvious that the most accurate results are obtained by using several different methods at the same time. Under good field conditions and in the absence of abiotic and biotic stresses, the theoretical potential grain yield of maize, characterised as a high-yield plant, was estimated to be about 25 t ha^{-1} under North American climatic conditions (Tollenaar 1983). In Europe, potential maize yield is slightly lower and can reach more than 15 t ha^{-1}, mostly in warm countries such as Portugal, Spain and Italy (www.yieldgap.org). The potential yield of maize crops in their marginal growing zones, e.g., in the Nordic-Baltic region, has often been modelled at a global scale; however, such results are not always precise and do not provide any information on how the models were calibrated and validated;

for this reason, rather often, the modelled yield is unreal. In Baltic States as well as in Sweden and Finland, maize is usually grown for biomass production. Hence, there is a lack of theoretical potential grain yield results based on modelled estimation under specific local conditions.

In high northern latitude countries, low temperature is a critical environmental factor for maize growth, and for a long time, the tolerance of low temperatures was an issue to be solved. Nevertheless, early-season cultivars facilitated maize growing under low temperatures (Riva-Roveda et al. 2016). Another problem associated with maize growing is water stress. Although Lithuania is a surplus area, i.e. the annual amount of precipitation exceeds evaporation, but due to climatic changes, short-term droughts are more frequent (Valiukas 2015). To separate the impacts of low temperature (cold) and water stress only with the help of field experiments is tedious and expensive. If the required model input parameters are available (for the majority of models, those parameters are experimental measurements of biomass, leaf area and soil water content), crop models can capture spatial and temporal variation in plant growth and quantify plant responses to cold and water stress. Nevertheless, it is rather complicated to simulate yield losses due to cold and water stresses, and such data is only theoretical, which depends on a variety of options such as base temperature for optimal growth. Experiments conducted in controlled environments helped to unravel the effects of temperature on crop development, growth and leaf photosynthesis. There has been some disagreement concerning base temperature for maize. Some researchers stated that the base temperature for maize growth and development is 6.2°C, while others indicated that it is 8°C (Sanchez et al. 2014, Fischer et al. 2014). Simulated yield losses due to water stress also depend on several factors which have to be set in the model, e.g., effective rooting depth. It is rather complicated and time-consuming to conduct those measurements in field experiments, but such data can be easily found in the literature. In field experiments, the gap between full NPK fertiliser plots (non-limited by nutrients) and plots without fertilisers (fully limited by nutrients) is used as a good diagnostic tool to assess the limitations of fertilisation rates and their impact on the productivity of the plants. However, optimum nutrient rates for maize are highly variable, and the demand of fertilisers changes over time; therefore, the optimum rates of fertilisers (especially organic fertilisers) have to be adjusted by year and location (Dhital and Raun 2016). To obtain maximum yields, large amounts of mineral and organic fertilisers are used. However, over-fertilisation does not always secure high yields and can result in substantial losses of nitrogen and phosphorus, an issue which is especially relevant in the Baltic Sea region, where the focus is currently placed on measures reducing nitrogen-leaching into surface waters (Andersen et al. 2014). Currently, most crop models make use of a nutrient-balance approach for modelling crop response to soil fertility stress (Van Gaelen et al. 2014).

1.6. Maize nutrition and fertilisation

During the last century, maize yield has significantly increased as a result of altered agronomic practices (nutrient and irrigation management, sowing dates, conservation tillage, pest control) and the breeding of new varieties (with increased kernel number and weight and a higher tolerance to abiotic stress) (Ciampitti et al. 2012). However, it is believed that the mechanisms associated with maize nutrient uptake and partitioning have not changed, and therefore, the increase in yield can be attributed to a higher total plant uptake and an increased nutrient removal (Bender et al. 2012). Over the past 70 years, there has been a significant increase in studies of various mechanisms in maize grain formation and its relationship with nitrogen uptake (Ciampitti and Vyn 2013). Previous research has established that maize plants take up more N before flowering than during the grain-filling period (Sayre 1948, Hanway 1962). Maize efficiently uses nitrogen accumulated before flowering because during foliar ageing, nitrogen is remobilised into the development organs, i.e. the grains (Feller and Fischer 1994). Nowadays, it is well known that among all the main plant nutrients, nitrogen is the most limiting factor in crop production in areas where water supply is adequate. When plants grow under N-limited conditions, growth is poorer and the leaves turn yellow, resulting in lower yields (Yang et al. 2012). Although the basics of maize nutrition were established in the last century, the requirements and behaviour of new varieties significantly differ from those of the old ones. For example, Ciampitti and Vyn (2013) confirmed that New-Era (1991–2011) maize hybrids are characterised by a greater yield, grain index and N uptake, likewise longer lasting green foliage and, furthermore, exhibit a greater tolerance to fertility stress than Old-Era (1940–1990) ones. Another difference among hybrids is that modern genotypes accumulate more N during the grain filling period and have a higher resilience to mid-season N stress (Mueller and Vyn, 2016). It is still not known how to find the balance between the nutritional needs in different plant growth stages and the mineralisation process of various fertilisers, including pelleted organic fertilisers.

Nutrient management is considered to be one of the most important means to increase grain yield and to reduce the fluctuation gap between potential and actual yield. Setiyono et al. (2010) claim that the nutrient requirements of maize are 16.4 kg N, 2.3 kg P and 15.9 kg K per 1 ton of grain. Similarly, Xu et al. (2013) showed that to produce 1 ton of spring maize grain, the nutrient requirements are 16.9 kg N, 3.5 kg P and 15.3 kg K. However, most crops, including maize, are location- and season-specific. Therefore, it is critical that realistic yield goals are set and nutrients are applied to meet target yields to benefit both farmers and the environment (Roberts 2008). Exaggerated N fertilisation is frequently used by farmers as a guarantee, but over-fertilisation can also result from over-estimation of expected yield despite the soil factors on which N-fertiliser recommendations are usually based. For instance, a meta-analysis of the results of N fertiliser experiments performed in Finland showed that the present fertiliser recommendations for spring cereals, which are based on the growers' yield expectations, can lead to substantial errors in N management practices (Valkama et al. 2013). In China, farmers still believe that large amounts of N fertilisers ensure high grain yield. Chen et al. (2011) generalised 43 high-yield experiments and revealed that on average, a fertilisation amount of 547 kg ha^{-1} N was used to obtain a grain yield of 15.2 t ha^{-1}, but maize N uptake was less than 300 kg ha^{-1}. Many studies have shown that combining organic and mineral fertilisers can balance balancing plant nutrition and maintain soil fertility (Abedi et al. 2010, Efthimiadou et al. 2010), thus reducing the risk of nutrients leaching into surface waters. In Lithuania, a comprehensive overview of the long-term studies is presented in the monograph "Management of agroecosystem components. Results of long-term agrochemical experiments" (2010) have revealed the significance of the use of organic fertilisers for plant and soil productivity and the risk of nutrient leaching. In countries with a cool northern climate, when growing short-vegetation maize varieties, it is possible to expect some specific reactions affecting the regularity of nutrition. However, agronomic research under cool climates, e.g., in Lithuania, has focused on maize grown for silage rather than for grain, and some specific issues, such as the impacts of different types of pelleted organic fertilisers, yield potential and potential drought episodes on grain maize yield, remain elusive. In Lithuania, very few field experiments were conducted to maximise biomass yield without relating maize growth and development with the use of nutrients and their translocation dynamics with the temperature regime, in particular under specific environmental conditions such as drought episodes.

1.7. Organic fertilisers

In the countries of the European Union (EU), including Lithuania, as well as in many other countries of the world, the aim is to keep the agro-ecosystems functioning in a sustainable manner. However, research shows that even in the EU, where a targeted regulatory and support system is applied, it is complicated to achieve satisfactory results (Stoate et al. 2009). In intensive specialised crop farms, plants are massively fertilised with mineral fertilisers; however, organic matter in the soil is constantly decreasing. On the contrary, in large livestock farms, excessive amounts of organic fertilisers are accumulated, with high emissions of nitrogen and other substances into the atmosphere and waters. Organic fertilisers are a well-recognised source of essential plant nutrients; however, their effects on soil fertility and crop yield vary widely and depend on the origin of the fertilisers, the fertilisation rate, and the time of application. The use of organic fertilisers is more complicated than the use of mineral ones, but the processing of manures provides a new perspective. In the EU, there are now 11 types of organic fertilisers that are produced from manure, but only three types of manure ("separation solids", "manure compost" and "dried manure and pellets") are marketed in higher quantities (Flotats et al. 2013). In general, manure processing technologies, including pelletisation, are becoming more popular, better developed and recognised in water and soil protection as well as in nutrient recovery. Pelletised manures offer opportunities for more comfortable logistics and management in some specific places of arable farms in regions with low soil organic matter levels. The effects of pelletised fertilisers differ greatly from those of unprocessed manure, depending on the processing type, livestock and soil conditions (Masayuki 2001). However, a better understanding of the metabolic processes in the anima´s body promotes a constant improvement of feeding rations (Drackley et al. 2006), thus changing the amount of faeces and their chemical composition and finally affecting the chemical composition of organic fertilisers and their efficiency. In Lithuania, as well as throughout the world, less attention has been paid to the short-term impacts of organic fertilisers when they were used at low rates in spring before sowing. However, the impacts of long-term fertilisation with the main types of organic fertilisers has thoroughly been researched, and the potential benefits and main risks are well known. Zavattaro et al. (2017) have analysed data of long-term experiments, covering a large range of European climate and soil conditions. Their results show that cattle manure produced slightly lower crop yields when used alone and higher yields when used in combination with N fertilisers such as ammonium nitrate. This study also showed that lighter soil texture, warmer temperature, and a longer mineralisation season were essential factors affecting crop yield in manure treatments. Poultry manure differs from cattle manure in a number of aspects; for example, regardless of being fresh or dried, poultry manure has a significantly greater first-year N availability and impact on grain maize yield (Muñoz et al. 2008). Although pelleted manure is more convenient to be used, it can differ in its characteristics from those of its raw components; therefore, when designing fertilisation plans, each year, the predicted N mineralisation and the synchronisation with the crop demand should be discussed (Hadas et al. 1983). However, it is still unclear which is the most suitable time to use pelleted manure, while it is known that liquid or poultry manure fertilisers are better to be used in early spring or before sowing in order to better balance nutrient release with the needs of the plant (Delin and Engström 2010). This is also the case for cattle manure, where the higher amount of N lies in organic compounds and thus, mineralisation is significantly slower. These processes suggest that plants should be fertilised in spring. In addition to traditional manure types, a wide range of wastes produced via municipal and agricultural activities can be used as a source of nutrients for agricultural plants. For instance, field experiments on sandy loam soil demonstrated that composts from biogas production, sewage sludge, waste or green waste can significantly increase spring barley grain yield and have an effect comparable to that of cattle manure (Staugaitis et al. 2016). However, the heterogeneity of the organic amendments suggests considering different N mineralisation patterns depending on quality parameters such as total N content, form of N, C/N ratio (Mohanty et al. 2013). Recently, Wiesmeier et al. (2015) indicated that in central and northern Europe, the regular use of organic fertilisers instead of mineral fertilisers can be an effective tool to reduce soil organic carbon losses and to overcome yield stagnation. Chivenge et al. (2011) investigated the effects of the combination of different mineral and organic nutrient sources on maize performance and concluded that yield responses increased with decreasing quality of organic source; a higher effect was observed on sandy soils compared to clayey soils. Generally, farmers have two main choices: the first is to rely on the first-year effect of organic sources with high N mineralisation potential, while the second is to combine organic fertilisers, which are characterised by slow mineralisation rates, with mineral nitrogen fertiliser. Nevertheless, poorly combined mineral and organic fertilisers can lead to over-fertilising and encourage leaching of nitrates and eutrophication of water bodies, especially in the Baltic Sea (Andersen et al. 2014). To successfully use the aforementioned strategies under specific local climatic and farming conditions, a better awareness of grain maize N economy and related traits is needed. Considering this, it seems that short- and long-term impacts of the different types of organic fertilisers on maize have already been extensively examined. However, there is still a lack of experimental evidence related to pelletised poultry and cattle manure as well as to the efficiency of green waste compost, especially in marginal maize growing regions.

1.8. Diagnostic tools for plant and soil N status

Fertilisation rates for plants, including maize, and grain yield vary from year to year and from location to location. It is known that each year, N rates at the same field vary mostly due to differences in the initial soil N supply, the variety and the hardly predictable environmental conditions. The issue is how to harmonise the plant's needs for nutrients in different development stages, and a potential solution to this problem is to use mid-season plant sensors than can indirectly and non-destructively assess nutrient deficiencies during vegetation growth. Recently, a wide range of tools has been proposed for monitoring plant N status, and various approaches in plant N nutrition studies have been tested. The chlorophyll index (SPAD), which is based on the indirect measurement of the chlorophyll content in leaves, has already become a classic nitrogen deficiency indicator. When using this method, the obtained values show leaf permeability in red light (wavelength 650 nm) and in near-infrared light (wavelength 940 nm), and the ratio of these two wavelengths is the SPAD reading (Hoel and Solhaug 1998). In recent decades, there have been a number of studies analysing the relationship between SPAD readings and plants N status. According to Piekielek et al. (1995), chlorophyll metre readings taken at maize experiments at the milking stage separated N-deficient from N-sufficient treatments with 93% accuracy. However, another study showed that the estimation of SPAD readings should be done after the growth stages V6–V7, because earlier measured SPAD readings and N concentrations in plants were not statistically related (Zebarth et al. 2007). A much-debated question concerning SPAD measurements is how to decide which leaf of the plant and which part of the leaf should be measured. Despite many different opinions, the majority of studies indicate that the measurements of the youngest fully expanded leaf best reflect plant N status (Rashid et al. 2005). Nowadays, there are more and more available tools for various plant measurements. For instance, the NIR spectrum can be used for a rapid and inexpensive examination of organic fertilisers and other materials (e.g., soil) and thus for the assessment of their efficiency in plant nutrition. However, current studies are still preliminary (Delin et al. 2012). Other authors indicate that different chemical elements have different effects on photo-chemical processes in the plant and therefore, chlorophyll fluorescence, which is now successfully used as an indicator of leaf aging and stress, could be used to identify nutrient deficiencies (Kalaji et al. 2014). Another option to evaluate N status in plants is through direct measurements in the field. Sadras and Lemaire (2014) provided a detailed summery regarding the well-established theory of dilution curves and nitrogen nutrition index (NNI). Generally, NNI is calculated during the plant vegetation cycle as the ratio between actual plant N concentration and critical N concentration. This theory was developed more than three decades ago (Lemaire and Salette 1984), and since then, the NNI index has been used for the majority of plants, including maize (Herrman and Taube 2004). The authors argue that direct quantification of the crop N status removes the need to explicitly account for soil N availability, mainly because NNI integrates N supply and demand, accounting for biomass-dependent changes in N concentration.

Another classical destructive method to optimise N management is the determination of nitrogen use efficiency (NUE), but several different definitions for this index were proposed; the study by Fageria et al. (2008) could be mentioned here as an example. Researchers defined the NUE index as a nutrient-efficient plant which produces economy yield with a certain amount of used or absorbed nutrients. Another frequently used method to estimate NUE in cereal production in based on the yield produced per unit soil N (Moll et al. 1982). Agronomic indices such as agronomic N efficiency (AE_N), partial factor productivity (PFP_N) and crop recovery efficiency (RE_N) also allow the estimation of N efficiency in cereal production (Dobermann 2005). Although there are plenty of different methods and ways to evaluate NUE, the majority of studies focused on how to increase N efficiency as well as crop yield. However, those various indices do not always evaluate the soil factor and might therefore not be comprehensive enough. Soil mineral N (N_{min}) content is a reliable, well-developed indicator of the plant nutrition status. To specify fertilisation rates, the amount of N_{min} is usually determined in spring before sowing, but varies greatly during the vegetation cycle due to N uptake, microbial activities or environmental conditions. During mid-season, that is prior to grain formation, the amount of N_{min} clearly indicates whether N limits plant growth. Besides, it can also be useful in predicting the yield. The amount of N_{min} in the soil can indicate not only N shortage, but also the excess which appears in over-fertilisation, potentially resulting in nitrate leaching to groundwater. Numerous studies indicate that over-fertilisation not always leads to additional grain yield, but instead increases the risk of N losses (Raun and Johnson 1995). Meanwhile, lower N rates can result in yield decrease (Scharf and Lory 2000). Combined, the application of the aforementioned means for monitoring variations in the N status of grain maize, receiving various types of fertilisers under cool conditions, is still limited. Therefore, to assess the effects of different fertiliser types on maize nutrition, traditional N indicators were taken into account (SPAD, NNI, AE_N, PFP_N, RE_N, PE_N, N_{min}).

In summary, the literature review showed that in the near future, grain maize expansion to the north will potentially increase. However, our limited knowledge concerning grain maize nutrition can constrain this development. The thorough literature review evoked several questions: 1. Are crop models suitable to simulate maize biomass and grain yield formation under unfavourable growing conditions in nemoral climate zones? 2. What is the yield potential of maize and which abiotic factors are responsible for the "yield gap" in this region? 3. What is the contribution of organic fertilisers of different origins on soil N supply and maize grain productivity? 4. Can organic fertilisers replace parts of ammonium nitrate without yield losses? 5. How well can mid-season plant and soil N status predict grain yield and soil N at harvest?

2. MATERIALS AND METHODS

To meet the established research objectives, two different research approaches were applied: field experiments (from 2015−2017) and crop modelling using AquaCrop and AgroC. The selected models mainly differed in their complexity and the required amount of input data. The obtained experimental data such as total above-ground biomass (TAB), canopy cover (CC) (instead of leaf area index), soil water content (SWC) at various depths, grain yield and other parameters (e.g., maize growth stages, groundwater level) were used as input data for the simulation of the formation of maize yield at different environmental conditions. To test the two growth models under distinct drought and cold conditions, data from 2015−2016 were used for modelling. This particular period was selected due to rather different weather conditions at this time. Comprehensive data of grain maize development and growth during field experiments allowed the use of two different models (AquaCrop: water-driven dynamics; AgroC: mechanistic and based on different sub models) and the comparison of the simulated results. The results of the field experiments and the modelling are interrelated and complement each other, i.e. modelling results help to understand fundamental biophysical mechanisms determining maize performance during water shortage or temperature stress conditions. The separation of these unfavourable factors via experiments is often troublesome and expensive.

2.1. Experimental location

The maize (*Zea mays* L.) field experiments were conducted from 2015−2017 at the Lithuanian Research Centre for Agriculture and Forestry, located in Akademija (55°39′ N, 23°86′ E), Central Lithuania (Fig. 2).

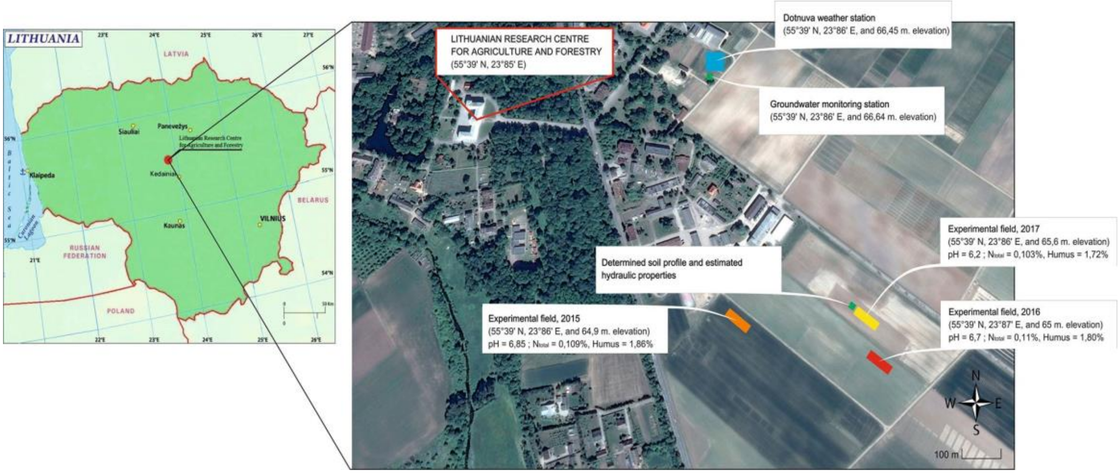

Figure 2. Location of the experimental sites at the Lithuanian Research Centre for Agriculture and Forestry in Akademija, Kėdainiai distr.

The area is characterised by intensive cash crop production regions. According to the Köppen climate classification (Kottek et al. 2006), the climate of the experimental site is humid continental (*Dfb*), with warm summers and rather severe winters. According to The Environmental Stratification of Europe, Lithuania is in nemoral climate zone the climate of which is characterized as continental and cool with a rather short vegetation period of plants. The Southeast territories of Estonia, Latvia and Northwest Belarus are also attributed to this climate zone (Metzger et al. 2012). Mean annual air temperature is 7°C with a mean annual precipitation of 557 (mean values over the 30-year period from 1981–2010). The soil is *Hypocalcic Stagnic Luvisol* (WRB 2014) (Fig. 3).

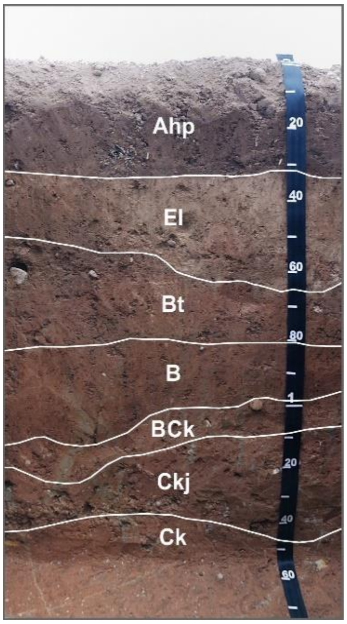

Figure 3. Profile of a *Stagnic Hypocalcic Luvisol*, 2017 (photo taken by Dr J. Volungevičius).

The main characteristics of the top soil layer (0–20 cm), measured at the beginning of the experiments in 2015, 2016 and 2017, respectively, were as follows: sandy loam texture (53.1, 53.0 and 55.0 % sand, 13.3, 15.0 and 13.1 % clay, 33.6, 32.0 and 31.9 % silt). The main soil agrochemical characteristics were neutral soil pH and relatively low organic matter content, with medium plant-available phosphorus and potassium levels (Table 1). Depending on the year, available nitrogen at the soil layer of 0–60 cm differed substantially and ranged from 10.7 mg kg^{-1} (2017) to 20.7 mg kg^{-1} (2016). The groundwater table in the area is relatively shallow and fluctuates between 194 and 289 cm throughout the growing season.

Table 1. Soil characteristics of the top soil layer (0–20 cm) and field management data.

	2015	2016	2017
Soil pH_{KCl} (1 N KCl extraction)	6.85	6.70	6.20
Soil P_2O_5 (mg kg^{-1}) (Egner-Riehm-Domingo, A-L)	154	129	85
Soil K_2O (mg kg^{-1}) (A-L)	138	140	154
Soil humus (%) (Tjurin)	1.86	1.80	1.72
Soil N total (%) (Kjeldahl)	0.109	0.11	0.103
NO_3^--N (0–30 cm) mg kg^{-1}	8.4 ± 0.9	9.4 ± 2.3	4.2 ± 1.2
NH_4^+-N (0–30 cm) mg kg^{-1}	1.8 ± 0.5	3.7 ± 1.4	2.5 ± 0.1
NO_3^--N (31–60 cm) mg kg^{-1}	4.3 ± 0.6	4.9 ± 0.7	2.2 ± 0.3
NH_4^+-N (0–30 cm) mg kg^{-1}	1.2 ± 0.3	2.7 ± 1.1	1.8 ± 0.4
Previous crop	spring rape	spring rape	winter wheat
Maize seeding dates	8 May	10 May	10 May
Maize harvesting	12 October	10 October	10 October

2.2. Maize management and treatment arrangement

An early-season, hybrid maize variety Agiraxx (characterized as FAO-190) was grown in 2015−2017. This variety was bred in France by the RAGT Seed Company (Saffron Walden, UK) and selected because of its early maturity and suitability to grown in Nemoral climate zone. It is characterized by a high dry matter allocation to the grains as well as a slow leaf senescence rate. In state trials in 2015-2017 this variety produced 7.69−9.46 t ha^{-1} of grain (14% moisture content), with vegetation period of 126−135 days after maize emergence. When the soil temperature reached 8–10°C, sowing was performed at a density of 7 plants m^{-2} (70,000 plants ha^{-1}, 0.75 m row spacing, 0.18 m plant spacing) at a depth of 6−8 cm. Prior to sowing, fertilisers were applied manually according to the protocol of the experiment and incorporated into the soil. Weeds were controlled by the herbicide MAISTER OD (rate 1.7 l ha^{-1}). Maize harvest was performed manually after the first autumn frosts. The experimental design included 10 treatments with different nitrogen sources and fertiliser levels (Table 2).

Table 2. Actual amounts of nitrogen, phosphorus and potassium applied in the different treatments (average 2015−2017).

Treatments	Nutrient rate kg ha^{-1}		
	N	P	K
Control (CON)	−	−	−
Ammonium nitrate N90 (AN90)	90	−	−
Ammonium nitrate N90 + P + K (AN1)	90	45	90
Ammonium nitrate N170 + P + K (AN170)	170	85	170
Pelletised cattle manure N170 (PCM)	170	90.0	318.1
Ammonium nitrate N90 + pelletised cattle manure N80 (AN + PCM)	170	42.3	149.7
Pelletised poultry manure N170 (PPM)	170	78.3	250.6
Ammonium nitrate N90 + pelletised poultry manure N80 (AN + PPM)	170	36.8	118.0
Green waste compost N170 (GWC)	170	93.7	220.4
Ammonium nitrate N90 + green waste compost N80 (AN + GWC)	170	44.1	103.7

In the plots of the treatments AN1 and AN170, superphosphate and potassium chloride were used to avoid P and K deficits. A randomised complete block design with four replicates was used. Each experimental plot had a total area of 30 m^2 (10 m length × 3 m width), and only the inner part of the plots, 12 m^2 (8 m length × 1.5 m width), were harvested. The pelletised cattle and poultry manures used in the experiments were manufactured by local producers. Pelletised cattle manure is made of solid cattle manure compost, which, after composting, was additionally dried, chopped and pelletised. Manufacturing process for the production of pelletised poultry manure is similar: the manure was bio-fermented and composted, the compost was matured in special storage places and subsequently, the minced compost was pelleted. Green waste compost was collected from a local landfill and consisted of plant residues. The residues were composted during a summer–winter period in special storage places for over 60 days. The main characteristics of the organic fertilisers are shown in Table 3.

Table 3. Chemical characteristics of pelletised cattle and poultry manures (PCM and PPM) and green waste compost (GWC).

	Content		
	PCM	PPM	GWC
pH	9.5	6.6	8.4
Dry matter %	82.3	81.1	70.3
In dry matter:			
Organic matter %	65.0	74.7	16.1
Total nitrogen (N) %	2.8	4.7	0.6
Total phosphorus (P_20_5) %	1.2	2.4	0.3
Total potassium (K_20) %	7.10	3.60	0.80

2.3. Plant measurements

During the maize vegetation period, plant development stages were recorded frequently. Maize vegetative and reproductive development stages were identified on the basis of the entire treatment when 50% or more of the plants were at a particular development stage. The leaf-collar method (Abendroth et al. 2011) was used for the development of vegetation stages, whereas reproductive stages are based on established visual indicators of kernel development. Maize total aboveground biomass was determined five times per growing season: at vegetative leaf stages 8 and 14 (growth stages V8 and V14), at the reproductive tasselling / silking and milking stages (growth stages VT/R1 and R3). In total, 20 selected plants from each treatment (five plants per replicate) were cut at the soil surface and separated into the main components (if present at the sampling date): leaf (leaf blades), stalk (stalk and leaf sheaths), reproductive part (cob and husk), tassel and grain. At physiological maturity (growth stage R6), when more than 50% of the plants showed a visible black layer at the base of the kernel, two central rows of each plot from an area of 8 × 1.5 = 12 m^2 were cut to identify final total aboveground biomass and grain yield. The individual maize components were weighed (fresh mass) and dried at 65 ± 5°C to constant weight (dry weight). Leaf area was measured five times per season (growth stages: V8, V14, VT/R1, R3, R6), using a CL 203 Handheld Leaf Area meter (CID® Inc, WA, USA); based on these results, the leaf area index (LAI) was calculated. For the model input parameters, LAI was converted into green canopy cover (CC), using an exponential function according to Hsiao et al. (2009):

$$CC = 100.5\,[1 - \exp(-0.60\,LAI)]^{1.2} \qquad [1]$$

2.4. Maize N status

The TAB samples taken at the growth stages V8, VT and R6 were used to define N, P and K concentrations. At the stages V8 and VT, N, P and K levels were determined in the entire plant. At physiological maturity (R6), nutrient content was determined only in the grain, while in remaining plant, TAB was measured. Total N was determined by the Kjedahl method. Accumulated N uptake in TAB and grain yield were calculated by multiplying the N concentrations by yields. The nitrogen nutrition index (NNI) at the vegetative growth stages was calculated by dividing the observed N concentration ($N_{observed}$) of TAB by the critical N concentration ($N_{critical}$), as described by Lemaire and Meynard (1997):

$$NNI = N_{observed}/N_{critical} \qquad [2]$$

where $N_{critical}$ is the minimum N concentration required for unlimited growth of the C4 maize species, determined as $N_{critical} = 3.4 \times W^{-0.37}$. Here, 3.4 is the minimum plant N concentration for W = 1 t ha^{-1} and −0.37 is the dimensionless coefficient for maize. When NNI = 1, nutrition is considered to be optimal, while NNI > 1 and NNI < 1 indicate nutrient excess or deficiency, respectively.

The agronomic N efficiency coefficient (AE_N) was calculated to analyse the performance of different treatments, as described by Dobermann (2005):

$$AE_N = (Y_N - Y_0) / F_N \qquad [3]$$

The partial factor productivity of applied N (PFP_N) was calculated as follows (Dobermann 2005):

$$PFPN = Y_N / F_N \qquad [4]$$

The crop recovery efficiency of applied N (RE_N) was estimated using the following equation (Dobermann 2005):

$$RE_N = (U_N - U_0) / F_N \qquad [5]$$

where Y_N = maize yield with applied N (kg ha^{-1}), Y_0 = maize yield (kg ha^{-1}) in a treatment with no N, F_N = amount of N applied (kg ha^{-1}), U_N = total maize uptake in aboveground biomass at maturity in a treatment with applied N (kg ha^{-1}), U_0 = total maize uptake in aboveground biomass at maturity in a treatment without N (kg ha^{-1}).

The chlorophyll index was measured non-destructively and periodically at the stages V5, V14, VT, R2 and R3, using a portable chlorophyll meter SPAD-502 (Minolta, Ramsey, NJ, USA). Ten plants were randomly chosen in each plot (in total, 40 measurements per treatment), and the youngest fully expanded leaf was measured.

2.5. Soil measurements and hydraulic properties

Each year before maize sowing, the soil nutrient status was assessed. For soil analysis, composite soil samples were taken from the top soil layer (0–20 cm) from 12 different locations within the field and soil pH, humus content, total nitrogen (N_{total}), plant available phosphorus (P_2O_5) and potassium (K_2O) were analysed. Composite soil samples for nitrate and ammonium nitrogen (N_{min} = $N\text{-}NO_3$ + $N\text{-}NH_4$) were taken from a depth of 0–30 and 31–60 cm. In addition, soil samples for N_{min} measurements from each plot were taken twice per growing season: in the period with the most rapid growth and after harvest. In each plot, the soil sample (300–400 g) consisted of four to five sub-samples, taken at randomly selected places and N_{min} was measured spectrometrically. All soil (and plant) chemical analyses were conducted in the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry in Kaunas.

In May 2017, 10 undisturbed soil samples of 250 cm^3 were taken from the major soil horizons at 15–20, 40–45, 70–75, 90–95 and 120–125 cm of depth (Table 8) and transferred to the Forschungszentrum Jülich GmbH, Germany, for soil analysis. Soil hydraulic properties were determined using the HYPROP® (UMS, München, Germany) method as described by Schindler et al. (2010), in combination with the WP4® Dewpoint Potentiometer (Decagon Devices, WA, USA). Saturated hydraulic conductivity (K_{sat}) was measured using the KSAT system from UMS (München, Germany). In this study, the difference between saturated water content and permanent wilting point is defined as available water content.

2.6. Soil water content

In the years 2015–2017, soil volumetric water content (SWC) was measured weekly at a depth of 0–10 cm, using a TRIME-FM2 TDR System (IMKO, GmbH, Ettlingen, Germany). In addition, SWC was determined on site using a specifically calibrated „Watermark“ soil moisture meter (Irrometer Company, Riverside, CA, USA), installed at 30 and 60 cm depth and replicated every 7–14 days. Hereby, measurements were performed after weather conditions had changed, i.e. after rainy days or after longer dry periods.

2.7. Climatic and groundwater data

Daily meteorological data, namely maximum (T_{max}), minimum (T_{min}) and average (T_{avg}) temperatures, precipitation (P, mm), relative humidity (%), wind speed at 2 m height (m s^{-1}) and actual duration of daily sunshine (hours), were collected from the Dotnuva meteorological station of the Lithuanian Hydrometeorological Service (Ministry of Environment), located ~500 m from the maize experimental field (55°39′ N, 23°86′ E, at 66.45 m elevation). The data were used to calculate the reference Penman-Monteith evapotranspiration (ET_0) (mm day^{-1}) according to Allen et al. (1998). Meteorological data of the period from 2015–2017 were compared to the climate normal of 1981–2010 (Table 4). The sum of growing degree days (GDD), expressed in °C for maize, was calculated by subtracting the base temperature (8°C) from the average air temperature:

$$0 \leq GDD = T_{avg} - T_{base} \quad [6]$$

Groundwater levels were observed by the Lithuanian Geological Survey (Ministry of Environment). The groundwater monitoring station was located at a distance of 5 m to the Dotnuva meteorological station.

Table 4. Monthly weather data for the 2015−2017 seasons.

Year	Month	T_{max} °C	T_{min} °C	T_{avg} °C	Difference	Total P, mm	Difference	Total GDD, °C
2015	May	21.9	1.1	11.4	−1.4	50.4	3.4	149.1
	June	26.0	5.6	15.1	−0.6	26.3	−34.7	215
	July	30.7	8.4	17.1	−1.0	57.6	−12.4	342.6
	August	35.0	5.5	19.7	2.5	5.6	−56.4	277.8
	September	28.8	2.5	14.0	1.8	66	19.0	181.3
	October	17.3	−4.5	5.9	−1.2	6.7	−42.3	27.4
				13.9	0.0	212.6	−123.4	1.193
2016	May	28.1	1.4	15.0	2.2	27.3	−19.7	185.7
	June	31.9	3.9	17.5	1.8	57.4	−3.6	293.6
	July	29.1	10.1	18.6	0.5	128.2	58.2	337.9
	August	29.7	8.1	17.1	−0.1	109.2	47.2	298.5
	September	26.4	11.4	14.0	1.8	8.7	−38.3	203.5
	October	18.6	−2.1	5.4	−1.7	87.9	38.9	20.8
				14.6	0.7	418.7	82.7	1.340
2017	May	27.0	−1.3	13.0	0.2	3.4	−43.6	133.7
	June	26.2	2.4	15.4	−0.3	71.9	10.9	235.0
	July	25.9	7.2	16.6	−1.5	136.9	66.9	271.5
	August	32.8	4.9	17.1	4.9	51.5	−10.5	279.5
	September	23.6	1.9	13.3	1.1	123.1	76.1	183.5
	October	17.0	−1.0	7.4	0.3	89.2	40.2	20.8
				13.8	−0.1	476.0	140.0	1.124

2.8. Statistical analysis

Grain yield, nitrogen uptake and soil N data over the three years were subjected to combined ANOVA as described by Petersen (1994). Significant differences between the experimental treatments were determined using Tukey's test at the 0.05 probability level. Linear correlation-regression analyses were performed to estimate the relationships between plant measurements and yield. The main calculations were performed with *SAS 9.4* (SAS Institute Inc., 2016).

2.9. Model descriptions

AquaCrop is a crop model used to simulate yield responses of major crops to soil water availability and has been developed by the Land and Water Division of the FAO. Generally, AquaCrop calculates final crop yield in four steps: step 1 – simulation of crop development, step 2 – simulation of crop transpiration, step 3 – simulation of above-ground biomass production, step 4 – simulation of crop yield (Raes et al. 2017). A full description of the AquaCrop model can be found in Raes et al. (2009), Steduto et al. (2009) and Hsiao et al. 2009. In this study, AquaCrop 6.0 version was used. The AquaCrop has mainly been developed for application purposes such as irrigation scheduling, and some of the parameters are not directly accessible. For example, diverse plant parameters are built in for different plants and cannot be changed if different varieties are used. Additionally, the soil compartment is simulated by a bucket approach, which is in general less accurate in predicting water flow and water availability in the soil (e.g., Herbst et al. 2005). Because water stress is not only triggered by the atmospheric boundary conditions (precipitation and evapotranspiration), but also by water drainage, water holding and capillary upward flow, e.g., from shallow groundwater, a soil description based on physical parameters might improve the overall yield predictions. AquaCrop simulates daily cumulative total aboveground biomass production (TAB) as follows (Raes et al. 2017):

$$\mathrm{TAB} = \mathrm{WP} \cdot \sum \left(\frac{Tr}{ET_0}\right) \qquad [7]$$

where Tr is the daily crop transpiration, ET_0 – the reference evapotranspiration, WP – the normalised biomass water productivity. When calculating crop transpiration, water stress (Ks) and temperature stress (Ks_{Tr}) are considered as follows:

$$\mathrm{Tr} = \mathrm{Ks}\ (\mathrm{Ks}_{\mathrm{Tr}} \times \mathrm{Kc}_{\mathrm{Tr},})\ \mathrm{ET}_0 \qquad [8]$$

where Kc_{Tr} is the crop transpiration coefficient. In AquaCrop, there are four water stress response coefficients that are interpreted as affecting the expansion of canopy cover, inducing stomatal closure and early canopy senescence and reducing harvest index (HI). Temperature stress is assumed to influence crop transpiration in AquaCrop, but not the final production. Water and temperature stress are indicated by thresholds at which plant growth starts to be stressed: an upper threshold, a lower threshold at which growth is fully inhibited by stress and a shape parameter that determines the extent of the stress effect on the processes of plant growth between these bounds.

The AgroC model has been developed as a scientific model based on different submodels for the soil compartment (SoilCO$_2$ (Šimůnek and Suarez 1993)), RothC (Coleman and Jenkinson 2008) for carbon turnover and the SUCROS model (Spitters et al. 1989) for plant growth. A detailed description of the AgroC model can be found in Herbst et al. (2008) and Klosterhalfen et al. (2017). In general, all parameters for the crop routines, soil and carbon are accessible and can therefore be modified according to the specific requirements of each study. Particularly, the soil compartment divergent from the bucket approach as implemented in AquaCrop. In AgroC, the Richards equation will be solved for the water flow, and the parameterisation of the soil hydraulic conductivity and the retention characteristics will be considered by the Mualem-van Genuchten approach (van Genuchten 1980). When estimating the actual transpiration T_a (cm d^{-1}), the soil pressure head h (cm) is taken into account. The reduction of the potential transpiration T_a to the dimensionless reduction factor α (−) according to Feddes et al. (1978) was applied:

$$T_a = T_P \alpha(h) \qquad [9]$$

The reduction factor α is estimated from four specified threshold heads, h_0, h_1, h_2 and h_3 (cm), as follows:

$$\alpha(h) = \begin{cases} \dfrac{h_0 - h}{h_0 - h_1} & h_0 \leqslant h \leqslant h_1 \\ 1 \qquad \text{for} & h_1 \leqslant h \leqslant h_2 \\ 10^{\frac{h_2 - h}{h_3}} & h_2 \leqslant h \leqslant h_3 \end{cases} \qquad [10]$$

where h is the soil pressure head at a specific soil depth. In this study, soil pressure head levels (h_0, h_1, h_2 and h_3) were set to 15, 30, 800 and 5,000 cm, respectively (Klosterhalfen et al. 2017). Profile depth α was averaged and weighted according to the normalised root density function to compute the water stress index α_{avg}, which was subsequently used to reduce the carbon assimilation rate according to water stress. For coherence with AquaCrop, α_{avg} was changed to water stress as $(1-\alpha_{avg})\cdot 100$. In AgroC, the observed air temperature affects crop development and growth via the degree-day method as well as the instantaneous assimilation rate.

2.10. Model parameterisation, calibration and validation procedures

For modelling maize growth and development, a treatment with mineral fertilisation (AN170) was selected to ensure optimal (no nutrient-limited) growth. Both models were calibrated on the experimental data of 2015 (dryer year) and validated on data of 2016 (wetter year). For the calibration of the AgroC model, a two-step procedure was applied (Klosterhalfen et al. 2017). First, plant growth and development were adjusted manually to reproduce maize phenology and cumulative TAB of the single organs in a reasonable way and thereafter, the soil-saturated hydraulic conductivity K_{sat} was measured. This was a requisite because the simulations based on the Mualem-van Genuchten parameters, measured from the HYPROP® data, and laboratory K_{sat} measurements did not adequatel reproduce the in-situ estimated soil water contents. Laboratory measurements of K_{sat} do not necessarily describe effective plot scale water movement due to spatial variability and changes in many orders of magnitude within short distances (Nielsen et al. 1973, Sharma et al. 1987, Loague and Gander 1990, Mohanty et al. 1994, Mohanty and Mousli 2000). For the calibration of K_{sat}, the global optimisation routine shuffled-complex-evolution of the University of Arizona (SCE-UA), as described by Duan et al. (1992, 1994), was used and the mismatch between observed (O_i) and simulated (S_i) water contents was minimised using the root mean square error (RMSE) according to Willmott (1982):

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(S_i - O_i)}}{n} \qquad [11]$$

Subsequently, the parameters describing plant development and growth were adjusted again by modifying the base temperature, the effectiveness of CO_2 assimilation and the partitioning factors of assimilates between different organs (leaf, stem, cob, grain) (Table 5). For the AquaCrop model, first the input parameters of CC (plant density, germination rate) were entered into the model and subsequently, the time of maize development, expressed in growing degree days (GDD), was adjusted (sum of GDD for emergence, max canopy, senescence, maturity); the parameters which indicate canopy expansion and decline were then modified (maximum canopy cover; canopy growth coefficient (CGC) and canopy decline coefficient (CDC)). Eventually, the coefficients (crop coefficient for transpiration (Kc_{tr}), crop water productivity (WP) and reference harvest index (HI)) which regulate dry matter (biomass and grain yield) and soil water content during the growing season period of maize growth were adjusted. In AquaCrop, GDD plays a paramount role in crop development and growth, considering that the calculation of GDD is based on the base and upper temperatures for the crop, and these two temperatures are principally dependent on the maize variety and the climatic conditions. When maize for grain is grown in a northern region, the accurate determination of these temperatures is quite sophisticated due to the lack of experimental results and the fact that producers of maize varieties do not provide such information. Hence, in this study, I used default values for base and upper temperature (8° and 30° C). A review of the parameters used for calibration in AquaCrop is provided in Tables 6–8.

Table 5. Standard settings and calibrated parameters for AgroC used in the simulation of maize growth at Akademija, Kėdainiai distr., Lithuania.

Parameters	Value		Units or symbol meaning	Remarks
Base temperature	8		°C	Conservative
Start temperature for plant growth	45		Sum of GDD	Calibrated
Specific leaf area of new leaves	0.004		ha leaf kg^{-1} dry matter	Calibrated
Potential CO_2 assimilation rate of a unit leaf area for light saturation	58		kg CO_2 ha^{-1} leaf h^{-1}	Calibrated
Initial light use efficiency	0.68		(kg CO_2 ha^{-1} leaf h^{-1}) (J m^{-2} s^{-1})$^{-1}$	Calibrated
Maximal rooting depth	1.0		m	Calibrated
Number of seedlings per area	7		m^{-2}	Measured
Leaf area of one seedling	0.000669		m^{-2} per seedling	Calibrated
Critical LAI for leaf death due to self-shading	4		ha ha^{-1}	Conservative
DVS against reduction factor of the maximal light assimilation rate	0	1.0	DVS = 1.0: Tasselling DVS = 2.0: Physiological maturity	Calibrated
	1.3	1.0		
	1.6	0.8		
	2	0.3		
Daily average daytime temperature against reduction factor of the maximum light assimilation rate	-10	0.0	Temperature in °C	Calibrated
	9	0.1		
	16	0.8		
	18	0.9		
	20	1.0		
	30	0.8		
DVS against fraction of dry matter allocated to the shoot	0.0	0.2		Calibrated
	0.1	0.3		
	0.2	0.6		
	0.4	0.6		
	0.5	0.6		
	0.7	0.7		
	0.9	0.9		
	1.2	0.9		
	2.0	1.0		
DVS against fraction of dry matter of the above ground biomass allocated to the leaves	0.0	0.6		Calibrated
	0.3	0.9		
	0.8	0.2		
	0.9	0.0		
DVS against fraction of dry matter of the above ground biomass allocated to the stem	0.0	0.0		Calibrated
	0.3	0.0		
	0.8	0.7		
	0.9	0.5		
	1.1	0.0		
DVS against fraction of dry matter of the above ground biomass allocated to the cob	0.0	0.0		Calibrated
	0.8	0.0		
	0.9	0.8		
	1.1	0.9		
	1.4	0.8		
	2.0	1.0		

Table 6. Standard settings and calibrated parameters for AquaCrop used in the simulation of maize growth at Akademija, Kėdainiai distr., Lithuania.

Parameters	Value	Units or symbol meaning	Remarks
Growth			
Crop water productivity	30.7	g m^{-2}, function of atmosphere CO_2	Calibrated
Stomatal conductance threshold p-upper	0.69	Fraction of TAW at which stomata start to close	Conservative
Stomatal stress coefficient curve shape	6.0	Highly convex curve	Conservative
Morphology			
Maximum effective rooting depth, Zx	1.0	m	Calibrated
Initial canopy cover	0.46	%	Calibrated
Maximum canopy cover	88	%	Calibrated
Canopy growth coefficient (CGC)	10.5	% day^{-1}	Calibrated
Canopy decline coefficient (CDC)	0.79	% decline per day due to leaf aging	Calibrated
Leaf growth threshold *p*-upper	0.14	as fraction of TAW, above which leaf growth is inhibited	Conservative
Leaf growth threshold *p*-lower	0.72	Leaf growth stops completely at p-lower value	Conservative
Leaf growth stress coefficient curve shape	2.9	Curve shape moderately	Conservative
Early senescence stress coefficient p-upper	0.69	Above this early canopy senescence begins	Conservative
Early senescence coefficient curve shape	2.7	Moderately convex curve	Conservative
Crop coefficient for transpiration Kc_{tr}	1.02	Full canopy transpiration relative to ET_0	Calibrated
Phenology			
Base temperature	8	°C	Conservative
Cut-off temperature	30	°C	Conservative
Time from sowing to emergence	45	Sum of growing degrees days (GDD)	Calibrated
Time from sowing to maximum CC	643	Sum of growing degrees days (GDD)	Calibrated
Time from sowing to start senescence	1110	Sum of growing degrees days (GDD)	Calibrated
Time from sowing to maturity	1200	Sum of growing degrees days (GDD)	Calibrated
Time from sowing to maximum rooting depth	582	Sum of growing degrees days (GDD)	Calibrated
Harvest			
Reference harvest index (HI_0)	50	%	Calibrated

It should be noted that at the field location, the soil profile had seven horizons (Fig. 3); however, the AquaCrop model can only take five soil horizons into consideration, in contrast to the AgroC model, which is not limited in this regard. Thus, the soil horizon number was reduced to five by merging morphologically similar horizons in order to obtain comparable simulation results. First, the B (0.80–0.97 m) and BCk (0.97–1.10 m) horizons were merged into the B horizon (0.80–1.10 m), mainly because the content of limestone >2 mm particle size was the only parameter differing between these two horizons. Similarly, the Ckj (1.10–1.30 m) and Ck (1.30–1.55 m) horizons were merged into the Ck-horizon (1.10–1.55 m) because of the similar hydraulic characteristics of these horizons and only a minor difference in terms of stagnation in the Ckj horizon. Soil hydraulic parameters such as permanent wilting point (PWP), field capacity (FC), volumetric water content or saturation (SWC− θ_s or SAT) and saturated hydraulic conductivity (K_{sat}) were estimated from the retention curve measured by the HYPROP® data, whereby FC was assumed to be the water content at a pressure head of pF 2.2 158.5 cm. For both models, the same meteorological data were used for the two sequential years 2015 and 2016. In simulating potential yield in both models, it is assumed that all factors such as air temperature, soil water content, fertilisation and management are non-limiting for potential grain maize growth. For the estimation of potential yield in AgroC, base temperature was set to 0°C and the reduction factor of the maximal light assimilation rate to 1 (no reduction due to low temperature); water stress was removed from the model. For the potential yield estimation in AquaCrop, cold stress, affecting crop transpiration, was not considered, as well as water stress.

3. RESULTS

3.1. Environmental conditions

Maize growth periods were similar in all three experimental years. Irrespective of this, the weather conditions differed significantly in terms of temperature and rainfall regime, and average grain yield among all treatments differed substantially with 6.47, 8.48 and 7.42 t ha^{-1} for the years 2015, 2016 and 2017, respectively. In 2015, the average air temperature from the 8th of May to the 12th of October was 14.7°C (sum of GDD 1,193°C), which was almost the same as the climate normal, but close to the minimum value of the first 16 years of the 21st century. In 2016, the average temperature for the period from the 10th of May to the 10th of October was higher with 15.9°C (sum of GDD 1,340°C), which was close to the maximum value for the 2000–2016 period. In 2017, the average temperature for the period from the 10th of May to the 10th of October was 14.9°C (sum of GDD 1,124° C), which was slightly higher than that in the 2015 season, but lower than that in 2016. The higher air temperature in 2016 resulted in a faster plant development, especially at the vegetative stage, which was approximately 5–10 days shorter than in 2015 and 2017 (Table 7). It should be noted that at the beginning of June (V5 growth stage), some leaves turned purple on the majority of the maize plants (50–70%) in all three years, which is most likely a result of changes in the leave pigments (anthocyanin) as a genetic response of early hybrid varieties to cool nights, because during that period, air temperatures dropped below 8°C. Approximately 14 to 18 days after this, the leaves fully recovered and turned green again, without any further consequences. Rainfall amounts and soil moisture conditions during the maize growing seasons were also contrasting. In 2015, the precipitation sum over the maize growing period was only 194.2 mm (66.5% compared to the climate normal), but 378.4 (129.6%) mm in 2016 and 448.8 (153.7%) mm in 2017. Especially the dry August of 2015, with only 5.6 mm of precipitation, influenced and slowed down maize growth at the R1 growing stage, whereby the lowest three to four leaves started to turn brown until they finally withered. In 2016 and 2017, due to sufficient soil moisture, withering of the plant's flag leaves was not detectable. In summary, in terms of the temperature and rainfall regime, the weather conditions in 2016 were favourable for maize growth, which could become typical of Lithuania in the near decades as a result of climate change. In contrast, the relatively cool and droughty weather in 2015 had an adverse impact on maize growth, while the cool, but wetter conditions in 2017 were typical for this region. In this sense, the season of 2015 is hereafter referred to as "cool and dry", the season of 2016 as "warm and wet" and the season of 2017 as "cool and wet".

Table 7. Maize growing stages and growing degree days (GDD °C) for the growing seasons 2015–2017.

	Growth stage							
	Year	VE	V2	V5	V10	VT/R1	R2	R6
Days after planting	2015	14	21	36	64	88	118	158
	2016	11	18	26	55	77	109	156
	2017	11	19	31	61	83	119	153
GDD (°C)	2015	41	76	164	408	615	966	1,193
	2016	53	106	208	482	702	1,032	1,340
	2017	48	107	171	412	626	969	1,124

Note. GDD – sum of growing degree days, Vn and Rn – maize development stages

3.2. Soil hydraulic characteristics

The assessment of the soil profile according to its hydraulic characteristics is directly related to the calculated water stress; therefore, it is necessary to determine these values to obtain adequate simulation results. Thus, soil hydraulic characteristics were estimated in order to quantitatively separate the effects of water stress and cold stress on maize growth and development (Tables 8 and 9).

Table 8. Soil horizons, texture and hydraulic properties of the experimental soil (input parameters for the AquaCrop model).

Horizon descript-tion	Particle size %			Textural class	Bulk density $\mathrm{g\ cm^{-3}}$	SWC ($\mathrm{cm^3\ cm^{-3}}$) at			TAW $\mathrm{cm^3\ cm^{-3}}$	K_{sat} $\mathrm{cm\ day^{-1}}$
	sand	silt	clay			PWP	FC	SAT		
Ahp	55	31.9	13.1	sandy loam	1.81	0.023	0.289	0.300	0.277	0.6
El	70.4	23.4	6.2	sandy loam	1.70	0.069	0.354	0.358	0.289	2.2
Bt	35	35.7	29.3	clay loam	1.73	0.122	0.317	0.342	0.220	6.1
B	57.5	22.6	19.9	sandy loam	1.68	0.083	0.343	0.351	0.268	62.0
Ck	54.4	31.6	14	sandy loam	1.96	0.062	0.234	0.245	0.183	3.2

Note. SWC – soil water content, PWP – permanent wilting point, FC – field capacity, SAT – saturation, TAW – total available water, K_{sat} – saturated hydraulic conductivity; **horizon description:** *Ahp* (0–0.30 m) – mineral surface horizon with an accumulation of humified organic matter, *El* (0.30–0.60 m) – mineral horizon in which the main features is loss of silicate clay, *Bt* (0.60–0.80 m) – mineral illuval horizon with accumulation of silicate clay; *B* (0.80–1.10 m) – mineral illuval horizon, *Ck (*1.10–1.55 m) – initial horizon with accumulation of paedogenetic carbonates

Table 9. Hydraulic properties of the experimental soil (θ_r = residual water content, θ_s = saturated water content, α = inverse air entry pressure, n = shape parameter, K_{sat} = saturated hydraulic conductivity) (input parameters for AgroC model).

Horizon description	Thickness (m)	θ_r ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	θ (cm^{-1})	n (−)	K_{sat} (cm day^{-1})
Ahp	0–0.30	0.000023	0.300	0.0016	1.78	0.6
El	0.30–0.60	0.000020	0.358	0.0007	1.68	2.2
Bt	0.60–0.80	0.000010	0.342	0.0034	1.26	6.1
B	0.80–1.10	0.000184	0.351	0.0011	1.51	62.0
Ck	1.10–1.55	0.000011	0.245	0.0019	1.41	3.2

Note. **Horizon description:** *Ahp* – mineral surface horizon with an accumulation of humified organic matter, *El* – mineral horizon in which the main features is loss of silicate clay, *Bt* – mineral illuval horizon with accumulation of silicate clay, *B* – mineral illuval horizon, *Ck* – initial horizon with accumulation of paedogenetic carbonates.

Additionally, the derived Mualem-van Genuchten parameters from the HYPROP® data (*more details in section 2.5*) were used to obtain soil water retention curves for the five different soil horizons representing the main horizons at the experimental site (Fig. 4).

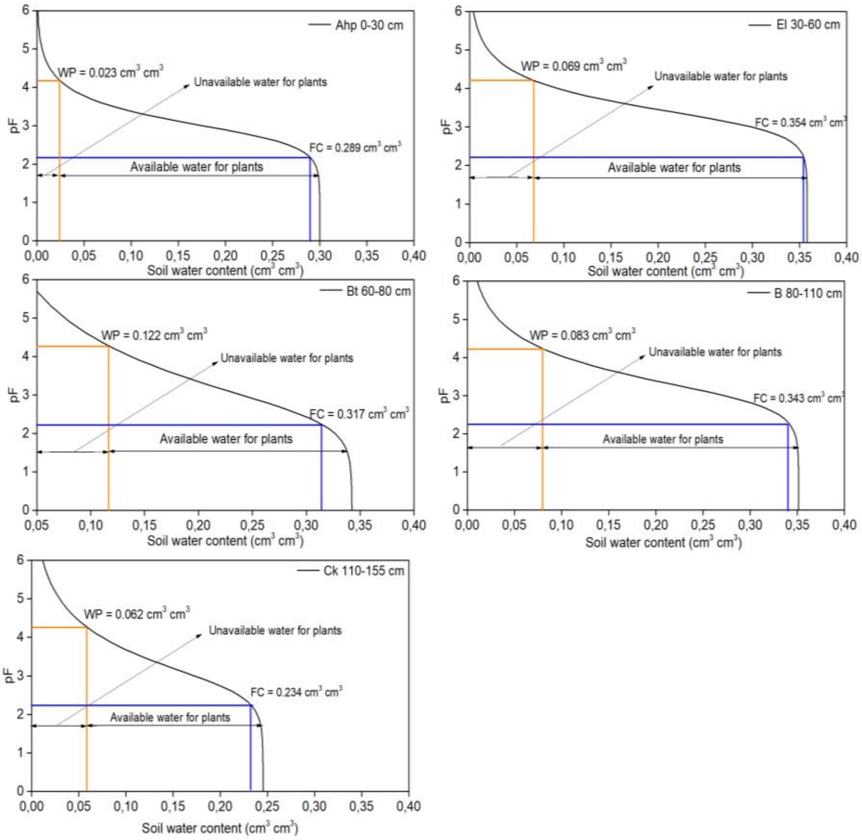

Figure 4. Soil water retention curves for the five different soil horizons. *FC* is field capacity, *WP* is the wilting point (all in $cm^3\ cm^{-3}$).

The SAT increased from 0.30 cm^3 cm^{-3} in the upper soil layer (Ahp-horizon) to 0.34–0.36 cm^3 cm^{-3} in the underlying El, Bt, and B horizons and declined substantially to 0.25 cm^3 cm^{-3} in the compact Ck horizon. The higher porosity or SAT in the El-horizon can be explained by the higher sand fraction (70.4%), while in the Bt and B horizons, it is a result of the secondary pore structure due to the aggregation in the soil. It worth noting that the Ahp horizon is very thick (30 cm), indicating ploughing and, consequently, the destruction of the secondary pore structure; it also shows that there is no erosion on the surface. This arable horizon is characterised by moderate sand contents (55%). The estimated PWP varied within the range of 0.02–0.12 cm^3 cm^{-3} and differed substantially between soil horizons.

Figure 4 indicates that the soil water-holding capacity of the experimental site is lower resilience to non-optimum water regime. A large and growing body of literature has investigated that water holding capacity regulates yield variability (Yang et al. 2014, Williams et al 2016). According to Minasny and McBratney (2017), the use or organic fertilisers not only increases the amount or organic matter in the soil, but also the soil water holding capacity.

3.3. Calibration and validation of the models

3.3.1. Partitioning of total above-ground biomass and grain yield

The results of the simulation of TAB (in dry matter) from AquaCrop and AgroC in comparison to the measured TAB are presented in Figure 5 for the two grain maize seasons. For simulating maize growth, the AN170 treatment was chosen to ensure growth is not N-limited. Both models reproduced TAB development over time relatively well. In the dry season 2015, the RMSE for AquaCrop was 0.69 t ha^{-1} ($R^2 = 0.98$, $p < 0.01$), while that for AgroC RMSE was somewhat larger with 0.86 t ha^{-1} ($R^2 = 0.97$, $p < 0.01$). In the wet season 2016, the corresponding values were 1.33 t ha^{-1} ($R^2 = 0.97$, $p < 0.01$) and 0.54 t ha^{-1} ($R^2 = 0.99$, $p < 0.01$) for AquaCrop and AgroC, respectively, indicating a better conformity for AgroC for the validation period compared to the calibration period. In 2015, at the time of harvesting, the measured TAB was 14.53 ± 0.65 t ha^{-1}, which was slightly underrated by AquaCrop with a simulated TAB of 14.05 t ha^{-1} (3.3% underestimation) and slightly overrated by AgroC with simulated 15.27 t ha^{-1} (5.1% overestimation). In the season more favourable for maize growth and development (2016), the measured TAB of 18.52 ± 0.75 t ha^{-1} was again slightly underestimated by 2.7% by AquaCrop (18.02 t ha^{-1}) and overestimated by 2.4% by AgroC (18.97 t ha^{-1}). Grain yields measured from field experiments in the dry season of 2015 and the wet season of 2016 were 6.85 ± 0.59 and 9.02 ± 0.71 t ha^{-1}, respectively (Table 10).

Table 10. Statistical values of the simulated vs. measured data for the calibration and the validation periods for rainfed maize at Akademija, Kėdainiai distr., Lithuania.

Parameters	Observed	Simulated		RMSE		R^2	
		AgroC	AquaCrop	AgroC	AquaCrop	AgroC	AquaCrop
			Calibration period				
CC (%)				11.7	7.02	0.71	0.99
TAB (t ha^{-1})	14.53 ± 0.6	15.27	14.05	0.86	0.69	0.97	0.98
Leaf (t ha^{-1})	1.21 ± 0.18	1.99	−	0.53	−	0.69	−
Stalk (t ha^{-1})	2.37 ± 0.21	3.54	−	0.79	−	0.56	−
Storage organs (t ha^{-1})	4.1 ± 0.38	2.81	−	0.96	−	0.95	−
Grain yield (t ha^{-1})	6.85 ± 0.59	6.93	6.90	0.44	1.01	0.98	0.92
SWC at 10 cm (cm^3 cm^{-3})				0.023	0.032	0.61	0.52
SWC at 30 cm (cm^3 cm^{-3})				0.016	0.021	0.48	0.41
SWC at 60 cm (cm^3 cm^{-3})				0.026	0.012	0.58	0.78
			Validation period				
CC (%)				17.02	4.01	0.76	0.97
TAB (t ha^{-1})	18.52 ± 0.7	18.97	18.02	0.54	1.33	0.99	0.97
Leaf (t ha^{-1})	2.26 ± 0.16	2.51	−	0.68	−	0.86	−
Stalk (t ha^{-1})	4.56 ± 0.44	4.52	−	0.42	−	0.91	−
Storage organs (t ha^{-1})	2.68 ± 0.41	2.93	−	0.61	−	0.31	−
Grain yield (t ha^{-1})	9.02 ± 0.71	9.01	8.93	0.35	0.89	0.99	0.98
SWC at 10 cm (cm^3 cm^{-3})				0.031	0.056	0.78	0.53
SWC at 30 cm (cm^3 cm^{-3})				0.018	0.023	0.69	0.66
SWC at 60 cm (cm^3 cm^{-3})				0.017	0.019	0.54	0.55

Note. CC – canopy cover, TAB – total above-ground biomass, SWC – soil water content

Similarly to the TAB measurements, grain yield disparities between the two contrasting seasons were apparent and can be partly explained by a high precipitation, especially during the grain filling stages, and a higher sum of GDD in 2016. This indicates that the climatic conditions, mainly air temperature and water availability, play an important role in maize cultivation in this climate zone. In both seasons, grain yield simulated with AgroC was slightly higher than that predicted with AquaCrop (AgroC: 2015 – 6.93 t ha^{-1}, 2016 – 9.01 t ha^{-1}; AquaCrop: 2015 – 6.90 t ha^{-1}, 2016 – 8.93 t ha^{-1}). Notwithstanding the rather contrasting growth conditions, the performance of both models in terms of simulation of TAB and grain yield can be considered as excellent or good. However, AquaCrop does not allow a perception of the development of different organs (e.g., stalk, leaves, cob) over the growing season, while AgroC provides plentiful information on the different organs, which helps to establish model parameters of the specific maize cultivar planted in the experiment. Under the favourable growing conditions in 2016, the measured final weights of the TAB components agreed quite well with the results simulated by AgroC. Measured leaf weight (basis on dry matter) was 2.26 ± 0.16 t ha^{-1} and simulated weight was 2.51 t ha^{-1}. Measured stem weight was 4.56 ± 0.44 t ha^{-1}, corresponding to a simulation result of 4.52 t ha^{-1}. The weight of the storage organs (shank, husk leaves and cob) was 2.68 ± 0.41 t ha^{-1}, and AgroC estimated 2.93 t ha^{-1}. However, in the unusually dry season of 2015, the similarity between measured and simulated values of the final weight of different components was not as high as in the wet season of 2016. In 2015, leaf blades attained the maximum weight at the end of the vegetative period in August and started to decrease ceaselessly due to increasing water shortage. At the tasselling (VT) growth stage, the lowest two to four plant leaves lost their green colour and withered, and therefore, their weight was not included in the total leaf weight. In 2016, the SWC was adequate to the maize requirements and the leaves stayed green and did not wither until the first autumn frosts; due to this, total leaf weight did not decrease until the end of physiological maturity. In 2015, stalk weight reached the maximum at the beginning of the reproductive period (August) and then started to decrease steadily, seemingly due to the reallocation of carbon and nitrogen compounds from the stalk to the developing ear, whereas in 2016, stalk and leaf weight did not decrease. In the wet year 2016, the share of storage organs in the total above-ground biomass was only 14.5%, while in of the dry year 2015, it was significantly greater (28.3%). This could be explained by the fact that in the dry year, the majority of plants produced a few cobs. Nevertheless, only one cob per plant was capable to reach an adequate size and physiological maturity. We enclosed non-matured cobs to the sum of storage organs. This separate incoherence of TAB components could not be reproduced by the AgroC model, which was only based on the differences in meteorological conditions in those contrasting seasons and neither included recovery effects between organs nor the loss of leaves after withering due to water stress conditions.

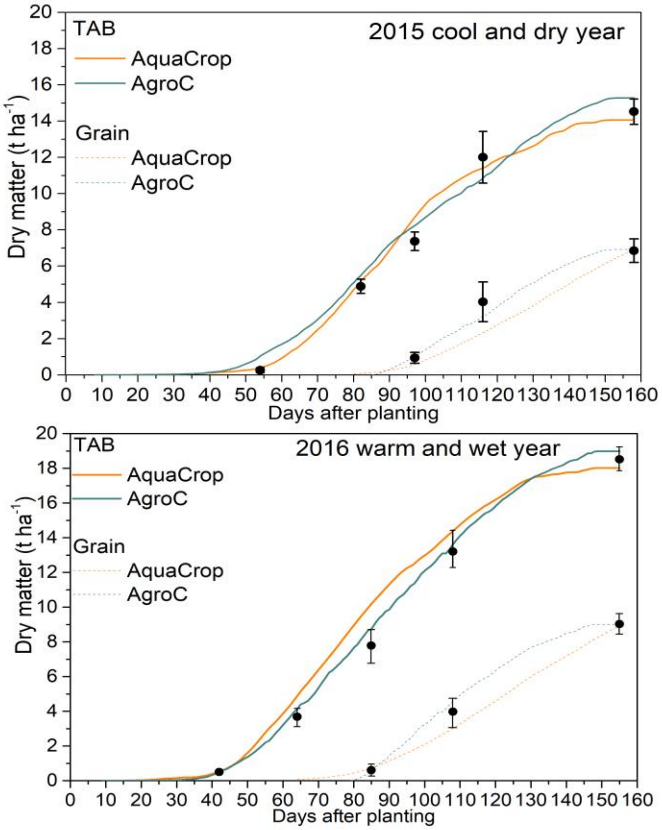

Figure 5. Comparison between measured (dots; error bars: standard error of the mean) and predicted (lines) total above-ground biomass (TAB) and grain as dry matter for the years 2015 (calibrated) and 2016 (validation).

3.3.2. Canopy cover development

The differences between the simulated and measured CC development for the two contrasting growing seasons are presented in Figure 6 and Table 10. AquaCrop does not predict LAI, and hence, leaf development is expressed as CC, the fraction of the soil surface covered by the canopy, whereas in the AgroC model, CC was replaced according to equation 1, using the simulated LAI. Without calibration (using only standard plant parameters), simulated CC (data not shown) values for both models were considerably lower than measured CC values. This can be explained by the phenological reaction of maize to the specific environmental conditions, especially to the impacts of temperature, rainfall and light (Liu et al. 2013). With increasing latitudes, the sum of GDD and the average air temperature required to reach a specific crop development stage are significantly lower than the standard default values might suggest due to the use of short-season cultivars. Thus, plant-specific parameters were adjusted considerably for adequate CC simulation. Both models, after calibration for the dry season in 2015, demonstrated a much better estimation of the CC for both growing seasons, whereby the AgroC model predicted higher CC percentages than measured at the beginning of each maize vegetation period. In comparison, the AquaCrop-predicted CC was lower than the measured CC for the year 2015 and similar to the measured CC in 2016. For later growing stages, both models were capable to adequately simulate the CC development in the year 2015, whereby AgroC was somewhat closer to the measurements than AquaCrop. Merely for the final measurement in 2015, CC was substantially underrated by AgroC, whereas AquaCrop was in good agreement with the measurements. This became different for 2016, where AgroC was able to simulate the last measurement, whereas AquaCrop could not, although the levels simulated by AgroC declined for the mid-season. Basically, both models sufficiently well predicted the seasonal trends in CC. For AquaCrop, the RMSE for the dry and wet seasons were 7.0% and 4.0% ($R^2 = 0.99$ and 0.97, $p < 0.01$), respectively, and for AgroC, the RMSE levels were slightly higher with 11.7% and 17.0% ($R^2 = 0.71$ to 0.76, $p < 0.01$), respectively.

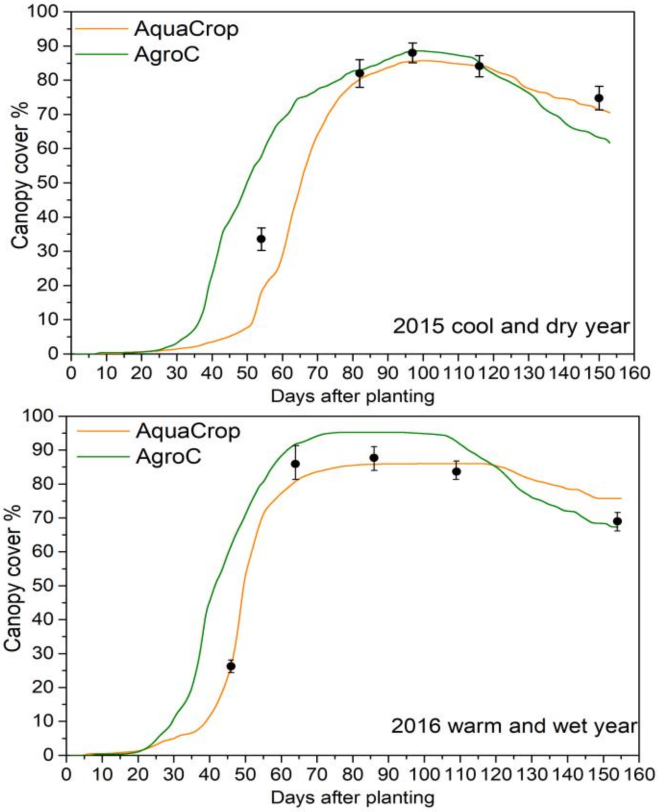

Figure 6. Measured (dots) and simulated (lines) canopy cover for the years 2015 (calibrated) and 2016 (validation).

3.3.3. Soil water content dynamics

The observed SWC for the three depths are shown in Figure 7. Additionally, the simulated SWC values after calibration of the soil hydraulic properties are plotted (calibrated and calculated soil hydraulic parameters as inputs for AquaCrop and AgroC are listed in Tables 8 and 9, respectively). As shown in the tables, AgroC matched quite well the SWC movements for both seasons for the measurements at a depth of 10 and 30 cm in the dry and wet years. Conversely, the AquaCrop model underrated SWC at these depths. It is worth noting that, although both models produced SWC levels similar to the measured ones, some peaks of SWC were not captured at the depth of 60 cm. In the dry season of 2015, AquaCrop estimated higher SWC values during the vegetation stage (VE–V8 stage) and lower values during the reproductive stage (R1–R2), while the AgroC model overrated SWC during the entire growing season. It is also obvious that in the wet year 2016, the measured SWC at a depth of 60 cm varied slightly throughout the vegetation period, which is in contrast to the modelling results which showed clear variations. The statistical values (R^2 and RMSE) showed that SWC values simulated by AgroC were slightly better at 10 and 30 cm in both years in comparison to the values simulated by the AquaCrop model (Table 10). The calculated errors for the AgroC model for the dry season (2015) were low, with RMSE values of 0.023, 0.016 and 0.026 $cm^3\ cm^{-3}$ for SWC at 10, 30 and 60 cm, respectively, and slightly increased to 0.031, 0.018 and 0.017 $cm^3\ cm^{-3}$ for the wet season (2016). The RMSE values for the AquaCrop model were higher than those for the AgroC model, with 0.032, 0.021 and 0.012 $cm^3\ cm^{-3}$ at 10, 30 and 60 cm for the calibration period and 0.056, 0.023 and 0.019 $cm^3\ cm^{-3}$ for the validation period. The calculated R^2 ($p < 0.01$) values were rather similar to those of the AgroC model, with 0.41 to 0.78 in 2015 and 0.53 to 0.66 in 2016. Generally, the results listed in Table 10 and illustrated in Figure 7 indicate that the AgroC model seems to be more adequate for reproducing the SWC variations in the field experiment presented.

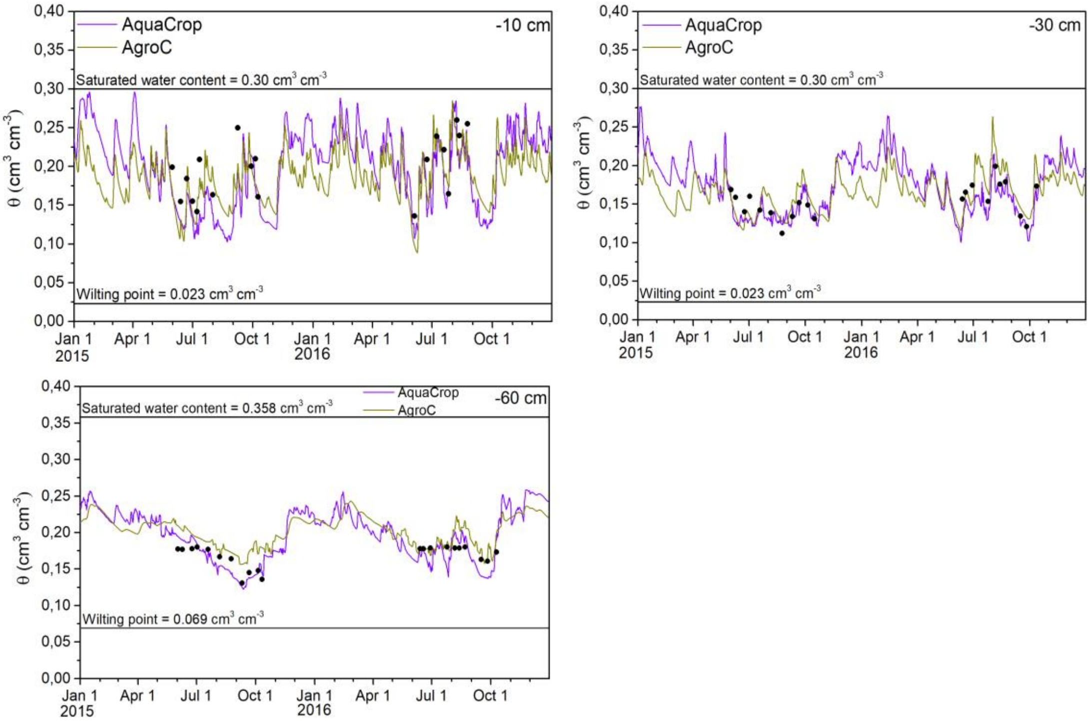

Figure 7. Comparison between measured (dots) and predicted (lines) soil water content, θ, (cm^3 cm^{-3}) at 10, 30 and 60 cm depth.

3.3.4. Maize response to cold and water stress

The results of the simulation of water stress in two contrasting growing seasons, using two different models, are shown in Figure 8. In both years, the occurrence of water stress and its intensity reflected the rainfall distribution over the growing season quite well. In 2015, during the vegetative stage, the quantity of rainfall was 126.8 mm; consequently, only a temporary water shortage occurred during the maize growth period. Comparison of the simulated water stress intensity suggests that both models provided comparable results, but interpreted the occurred water stress in somewhat different ways. The AquaCrop model specified mild water stress through the emergence-tasselling stage (VE-VT growing stages), expressing it as up to a 12% decrease in leaf expansion. Water stress simulated by the AgroC model, described as the ratio between actual and potential transpiration (1 indicating no water stress and 0 full water stress), was within the range of 0–27%. Rainfall during the reproductive period was as low as 67.4 mm, triggering significant water shortage in maize. Both models provided a resembling pattern of water stress occurrence, with maximum values at the blister stage (R2) and comparable water stress intensity (~42% in AquaCrop and ~49% in AgroC). In 2016, the amount of rainfall was sufficient during the entire maize growing cycle (211 mm at the vegetative and 167.4 mm at the reproductive period), with only occasional mild water stress. Throughout the vegetative period, the AquaCrop model estimated up to 11% water stress, mainly at the early growth stages, while AgroC estimated somewhat higher levels of water stress (2–30%). During the reproductive growth stage, no water stress was estimated by the AquaCrop model, and only transient episodes of mild water limitation were predicted by the AgroC model (0–11.3%).

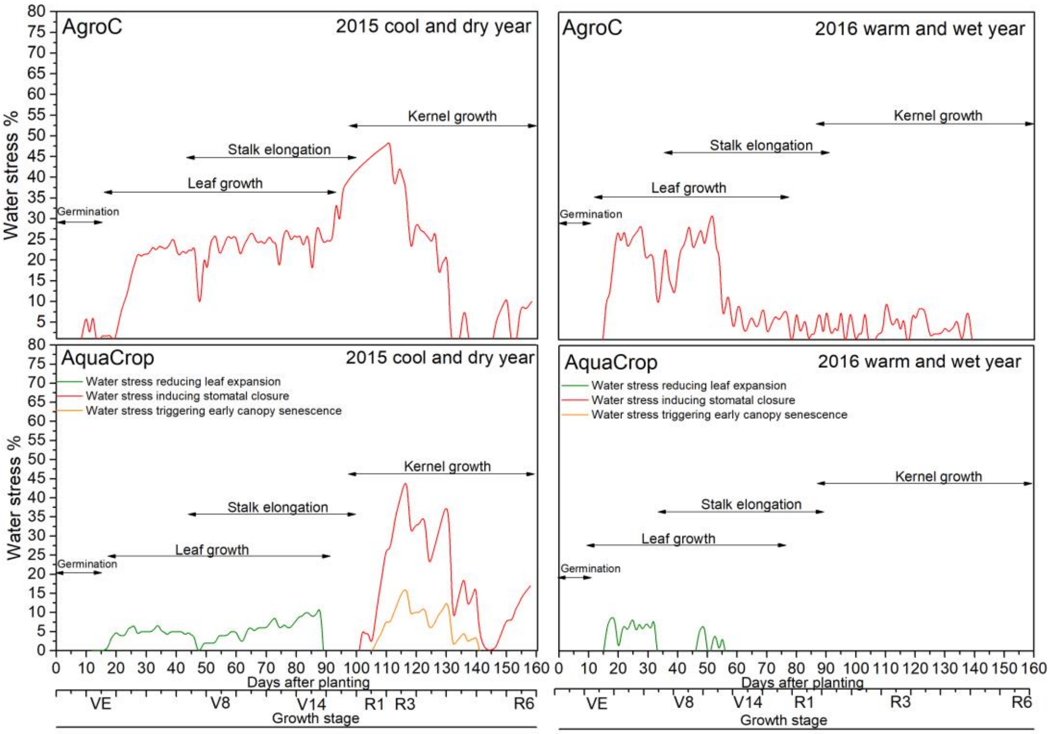

Figure 8. Predicted water stress intensities using AquaCrop and AgroC models in two contrasting growing periods.

Subsequently, the predicted yield potential of grain maize for the two contrasting periods was compared to the potential yield without water stress. Hereby, the grain yield losses due to water shortage in 2015 were essential. The AquaCrop model detected a yield gap between potential and actual yield of 0.81 t ha^{-1}, and AgroC estimated an even larger gap of 1.93 t ha^{-1} (Table 11). Even in the growing season with favourable climatic conditions (2016), grain yield losses due to water limitation were still perceptible, but two times lower than in the unfavourable year of 2015. Estimated yield gaps for the AquaCrop and AgroC models were 0.48 and 0.94 t ha^{-1}, accordingly.

As expected for these high-latitude regions, low air temperature (below 8°C) can be an important limiting factor of maize growth and development. In 2015, days with average temperatures below 8°C accounted for 28.2% and 24.6% of the days during the vegetative and reproductive stages, respectively. In accordance with the yield gap caused by water stress, the yield gap caused by low temperatures was also calculated. The results showed that yield losses due to low temperatures in 2015 were 2.60 and 2.39 t ha^{-1} for AquaCrop and AgroC, respectively. In 2016, days with low temperatures accounted for only 18% during the vegetative stage, but were nearly the same (25.3%) during the reproductive stage compared to 2015. As a consequence, potential grain yield losses in 2016 were lower than in 2015, with only 1.54 and 1.90 t ha^{-1} for AquaCrop and AgroC, respectively. This indicates that temperature stress during the vegetative stage is the dominant factor for potential yield losses at this location. The combined water / temperature stress yields in comparison to potential yield indicate that AquaCrop predicts a slightly smaller yield reduction due to water and temperature stress, with 3.41 and 2.02 t ha^{-1} for 2015 and 2016 compared to AgroC with 4.32 and 2.84 t ha^{-1}, whereby this gap is mainly caused by the higher potential yields predicted by AgroC.

Table 11. Simulated potential and actual grain maize yields and relative losses for the contrasting growing conditions in 2015 and 2016.

	2015		2016	
	AquaCrop	AgroC	AquaCrop	AgroC
Simulated yield				
Potential yield t ha^{-1}	10.31	11.25	10.95	11.85
Water-limited yield t ha^{-1}	9.50 (−7.9%)	9.32 (−17.2%)	10.47 (−4.4%)	10.91 (−7.9%)
Temperature-limited yield t ha^{-1}	7.71 (−25.2%)	8.86 (−21.2%)	9.41 (−14.1%)	9.95 (−16.0%)
Water / temperature limited yield t ha^{-1}	6.90 (−33.1%)	6.93 (−38.4%)	8.93 (−18.4%)	9.01 (−24.0%)
Average yield in Lithuania				
Actual yield (grain maize + cob mix) t ha^{-1}	4.81		6.94	

Note. Potential yield – yield of Agiraxx variety without nutrient, temperature and water limitation and with effective control of pests, diseases and weeds.

In summary, it is not possible to clearly discern the effects of low temperature and water shortage on grain yield through experimental data only. *Simulations indicate the importance of both of these factors, whereby cold stress seems to be the most important factor in the experimental region. This assumption is in agreement with literature evidences that in northern Europe, cool temperatures, mainly caused by late frost in spring, damage the crop stands sustainably, and that the overall short growing seasons are the main limitations for grain maize cultivation, but drought events are also a concern (Olesen et al. 2011). Unfortunately, both models used only simulated cold stress, but were not able to clarify the effects of low temperature-induced permanent damages of plant organs (e.g., leaves, stem).*

The observed difference in terms of the actual yields between the two years was 31% in Lithuania (Table 11), which agrees nicely with the findings of our study and *indicates potentially large year-to-year variations. The model precision must to be discussed against the background of the fact that for both models, the maize parameters were calibrated by hand (manually). In this case, the model results always reflect the decisions of the model user (Diekkrüger et al. 1995). In this model comparison, AquaCrop performed slightly better in terms of the estimation of CC/LAI, while AgroC showed a slightly better coincidence in terms of the estimated soil water content. This improved the simulation of water contents, which finally influenced the estimation of root water uptake stress; however, it is connected to a greater cost in terms of the measurement and inversion of soil hydraulic parameters. In addition, the higher complexity in the output data regarding the dry matter weights of plant organs provided by AgroC requires supplementary input parameters. The issue if a more complex or rather simple model should be used comes down to the availability of input data and measurements. A well-characterised experimental site, accompanied by a large number of continuous measurements, allowed the application of both model types. Complex and flexible models such as AgroC increase the spatial application range, permitting the analyses across a broader range of environmental conditions and crop traits. Also, this study provides additional support that AquaCrop can be used as an efficient tool to improve our understanding of fundamental biophysical mechanisms determining crop performance in water-limited or cold stress conditions. Both models approve in their results regarding the larger effect of cold stress in relation to water stress. Of course, the quantification of this effect depends on the chosen simulation approaches. For instance, in AgroC, the estimated water stress depends on the estimated amount of potential evapotranspiration, on the plant conversion factors* A_{kc}*, on the Feddes parameters and also on the soil hydraulic parameters. The cold stress is induced by the selection of the base temperature, and the estimated assimilation is also influenced by the temperature-dependency function.*

Notably, despite the fact that the two models differ essentially in their simulation approaches, both models agreed quite well in their responses to cold and water stress. This provides some reliance to our simulation results regarding the cold stress and water stress responses of maize.

3.4. The effects of different fertilisers on maize nutrition conditions and total above-ground biomass formation in the vegetative growth stage

Maize growth and development can be divided into two broad parts: vegetative (V) and reproductive (R). During the vegetative phase, maize forms foliage, stalks and storage organs and grows relatively rapidly. This growth stage also determines the potential cob size, influencing the potential kernel number. Maize growth can be described as the increase in the number of leaves, in stem size and in storage organs. At this stage, maize growth is fuelled by photosynthesis, thus growth directly depends on light interception. During the vegetative part, maize accumulates the larger part of nutrients that are used for the remaining life cycle; about two thirds of nitrogen, one third of phosphorus and four fifths of potassium. Generally, the maize vegetative stage determines the level of potential yield, and any shortages of nutrients, water or temperature stress can result in reduced yield. In this study, the following indicators were selected: Total above-ground biomass (TAB), leaf area index (LAI), nitrogen concentration, nitrogen nutrition index (NNI), chlorophyll meter (SPAD) readings, nitrogen uptake (N uptake) and soil N mineral content (N_{min}), as they are significantly affected by fertilisation and can identify various deficiencies, e.g., nitrogen deficiency.

3.4.1. Maize growing period from emergence to tasselling (growth stages VE–VT)

Total above-ground biomass (TAB). Maize TAB accumulation at the beginning of the vegetative period (V8) reflected the weather conditions, particularly the temperature regime, and was somewhat limited by low night temperatures. In all experimental years, no significant differences among treatments were found: the amount of TAB at the V8 growth stage was on average 0.261 t ha^{-1} in 2015, 0.336 t ha^{-1} in 2016 and 0.247 t ha^{-1} in 2017. However, as can be seen in Figure 9, the differences in TAB accumulation among treatments were noticed at the V14 growth stage. Despite some disparities between the years, at the V14 growth stage, accumulated TAB in the plots with organic fertilisers (except GWC) was typically 8.1% higher than that in the unfertilised plots. The corresponding values in plots with combined AN and organic fertilisers were 13.1% higher than those in the CON plots. On average (2015–2017 years), the highest TAB increase in comparison to CON treatment (27.7%) was observed in plots supplied with AN170.

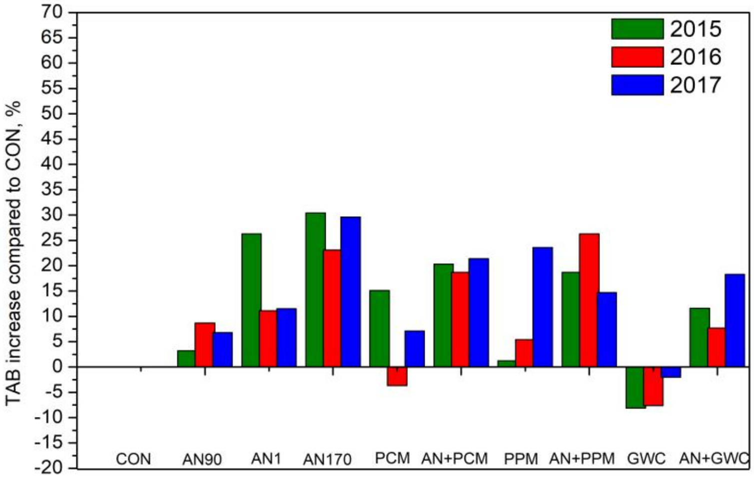

Figure 9. Total maize above-ground biomass accumulation at the V14 growth stage in 2015–2017 as affected by mineral and organic fertilisation.

Leaf area index (LAI). When the maize plants had their first eight leaves collared (V8), in all experimental years, LAI was still relatively low (values below 0.7). There were no statistically significant differences between treatments at that time. At this stage, the two lower leaves began to partially decompose due to the rapid growth of the stalk and secondary root system (brace root) formation. When maize fully developed the 14th leaf (V14), some differences in LAI among treatments were noticeable (Fig. 10); however, significant differences were established only in 2016. When compared to 2016, in 2015 and 2017, the average LAI was relatively low among all treatments with 2.13 and 2.51, respectively. These differences were possibly influenced by the different temperature regimes during the vegetative stages. Specifically, the average air temperature in 2016 before maize flowering was approximately 2°C higher than that in 2015 and 2017.

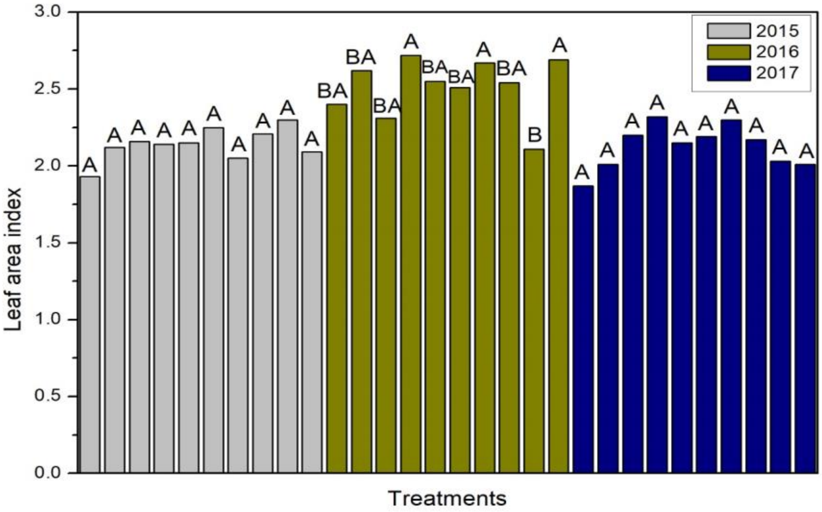

Figure 10. Leaf area index values of all experimental treatments at the V14 growth stage of maize. Treatments in the figure are arranged in the same order as indicated in the methodology (CON….AN + GWC). Different letters indicate statistically significant differences (P <0 .05, Tukey's test) within each treatment.

Chlorophyll meter (SPAD) readings. In the early stage of maize leaf growth (V5), the average SPAD values were similar, and no significant differences among treatments were detected. Significant differences among treatments were only noticed approximately 3 weeks before maize flowering (Table 12). In all experimental years, the highest SPAD values were measured in the AN170 and the AN + PCM plots. In contrast, the lowest SPAD values were typical of GWC, PCM and CON plots. Generally, SPAD values in the years 2015–2017 at the V14 stage ranged from 41.5 to 53.9, and these values are slightly lower than those reported in a previous study (Gao et al. 2017).

Table 12. SPAD values of the youngest fully expanded maize leaf at the V14 growth stage in 2015−2017.

Treatment / year	2015	2016	2017
CON	41.5 C	49.4 C	45.4 B
AN90	49.8 BA	53.6 A	49.4 BA
AN1	51.3 BA	50.6 BC	49.1 BA
AN170	53.9 A	53.2 A	49.0 BA
PCM	42.5 C	49.5 C	48.0 BA
AN + PCM	50.0 BA	52.8 BA	50.2 A
PPM	45.7 BA	52.5 BA	50.4 A
AN + PPM	50.1 BA	52.6 BA	48.7 BA
GWC	41.5 C	48.3 C	47.7 BA
AN + GWC	49.2 BA	52.2 BA	47.5 BA

Note. Different combinations of letters indicate significantly different means ($p < 0.05$, Tukey's test).

Nitrogen concentration and nitrogen nutrition index (NNI). The first measurements at the V8 growth stage showed no significant differences among treatments in terms of N concentration (Table 13). The variation of N concentration at stage V8 was in a range of 3.2–3.9% in 2015, 3.3–3.5% in 2016 and 3.0–3.8% in 2017. As expected, there were no statistically significant differences among treatments in NNI estimation at the V8 growth stage. However, the results suggest that at this growth stage, maize N nutrition in all treatments was insufficient. In the years 2015–2017 at stage V8, NNI varied from 0.55 ± 0.01 to 0.71 ± 0.03; higher NNI values were measured in the treatments with AN (NNI 0.67–0.71), while in the treatments with organic fertilisers, only NNI values were lower (0.55–0.64).

Table 13. Mean values of nitrogen concentration of leaves at the V8 growth stage of grain maize.

Treatments	2015	2016	2017
CON	3.3 ± 0.3	3.3 ± 0.1	3.0 ± 0.1
AN90	3.6 ± 0.1	3.4 ± 0.2	3.5 ± 0.1
AN1	3.7 ± 0.1	3.5 ± 0.1	3.3 ± 0.1
AN170	3.7 ± 0.1	3.5 ± 0.2	3.5 ± 0.2
PCM	3.4 ± 0.2	3.4 ± 0.1	3.3 ± 0.1
AN + PCM	3.8 ± 0.1	3.4 ± 0.1	3.6 ± 0.2
PPM	3.5 ± 0.1	3.5 ± 0.1	3.6 ± 0.1
AN + PPM	3.9 ± 0.1	3.4 ± 0.1	3.6 ± 0.2
GWC	3.2 ± 0.2	3.5 ± 0.1	3.1 ± 0.2
AN + GWC	3.7 ± 0.1	3.4 ± 0.1	3.8 ± 0.2

Note. ± – standard error

3.4.2. Maize nutrition and soil N status at mid-season (growth stage VT)

Total above-ground biomass (TAB). At mid-season (VT), maize TAB varied from 4.09 to 6.99 t ha^{-1} in 2015, from 4.68 to 6.18 t ha^{-1} in 2016 and from 5.09 to 6.78 t ha^{-1} in 2017. It is worth noting that the average percentage of TAB accumulation from sowing to tasselling (or mid-season) was 39.1% in relation to that at harvest, and these results are in line with Bender et al. (2012). In plots in which organic fertilisers were the only additional source of nutrients (except GWC), the accumulated TAB increased on average by 11.7%, while in plots receiving a combination of mineral and organic fertilisers, TAB increased by 24.6% as compared to unfertilised plots (Fig. 11). Similar to the V14 maize growth stage, the highest TAB increase (33.9%) was observed in plots supplied with AN170. Among the different experimental years, the TAB variation differed, in which was particularly evident in the cool and dry year 2015. This can be explained by the fact that N deficiency (lower NNI values in 2015) in unfavourable environmental conditions caused a significant reduction in maize growth, which was particularly evident in the organic treatments, while the efficiency in treatments with ammonium nitrate was stable throughout the experimental period, resulting in remarkable differences in TAB accumulation among all treatments.

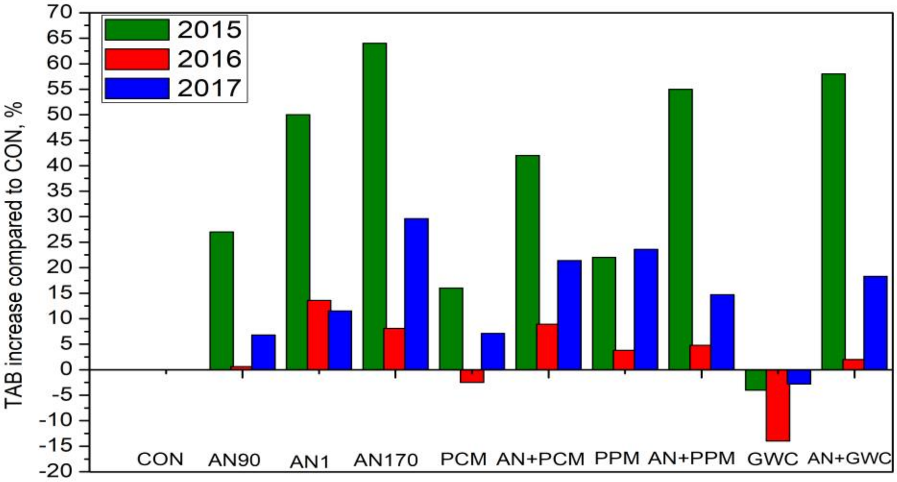

Figure 11. Total maize above-ground biomass accumulation at the VT growth stage in 2015−2017 as affected by mineral and organic fertilisation.

Leaf area index (LAI). The LAI reached the maximum values at mid-season, with similar values across all experimental years, on average, 2.8 in 2015 and 2016, 2.9 in 2017. The relatively low values of maximum LAI can be explained by the fact that the early-season hybrid under Lithuanian climate conditions produces only up to 14 leaves, while in their traditional growing regions, most Corn Belt hybrids can produce from 19 to 20 leaves (Abendroth et al. 2011). Furthermore, many studies have shown that LAI depends not only on the variety, but also on other factors such as planting date, location and leaf N content. For example, a study by Vos et al. (2005) confirmed that maize leaf N content, photosynthetic capacity and, ultimately, radiation use efficiency are more sensitive to nitrogen limitation than leaf area expansion and light interception. Therefore, growing maize in a cool climate zone and especially under limited N supply conditions, a smaller leaf surface area shall be expected.

Chlorophyll meter (SPAD) readings. The SPAD readings, which can rapidly and non-destructively estimate the nitrogen nutrition status, reached the plateau at the VT growth stage and, it was possible to rank the treatments accordingly (Table 14). In the wet years (2016 and 2017), the variation in SPAD values was lower than in the dry year (2015). However, in each of the three years, two distinctive groups appeared, with higher SPAD values in AN170, AN + PCM, AN + PPM, AN + GWC, AN90, AN1 and PPM and lower values in PCM, GWC and CON treatments. Generally, at the tasselling stage, the SPAD values were on average 15.6% higher in the combined treatments with organic fertilisers compared with CON. The corresponding results for the AN170 and PPM treatments were similar, with increased SPAD values of 16.5% and 13.5%, respectively. There were no significant differences between CON and organic (PCM and GWC) treatments.

Table 14. SPAD values of the youngest fully expanded maize leaf at the VT growth stage in 2015−2017.

Treatment / year	2015	2016	2017
CON	43.9 C	54.8 C	55.0 DC
AN90	55.1 A	59.8 BAC	61.2 BA
AN1	55.6 A	63.2 A	59.7 BC
AN170	56.5 A	61.8 BA	60.7 BA
PCM	44.9 C	56.9 BC	52.6 D
AN + PCM	54.5 A	62.5 BA	62.4 A
PPM	51.1 BA	61.2 BA	62.2 A
AN + PPM	55.5 A	60.8 BAC	61.8 BA
GWC	44.6 C	55.9 BC	53.6 DC
AN + GWC	54.1 A	59.4 BAC	62.1 A

Note. Different combinations of letters indicate significantly different means ($p < 0.05$, Tukey's test).

Nitrogen concentration and nitrogen nutrition index (NNI). On average, across all treatments, measured maize N concentrations differed between the years, with 1.7% in 2015, 2.4% in 2016 and 2.5% in 2017. Thus, estimated NNI values again provided distinct results in the three contrasting years. In the cool-dry year 2015, the NNI values varied widely (from 0.66 ± 0.03 in CON to 1.14 ± 0.02 in AN + GWC), indicating a stronger maize dependency on readily available nitrogen, namely ammonium nitrate (Fig. 12). Under more favourable conditions in 2016, NNI values in CON plots were substantially higher than in 2015, resulting in a narrower range among treatments (from 0.83 ± 0.02 in CON to 1.11 ± 0.02 in AN + GWC). In the cool-wet year 2017, the NNI values varied similarly as in 2015 (from 0.71 ± 0.03 in CON to 1.10 ± 0.02 in AN + GWC). In general, the NNI values suggest that in all years, maize N nutrition in AN170, AN + PCM, AN + PPM and AN + GWC plots was sufficient or even excessive (NNI > 1). Maize N nutrition in AN90, AN1 and PPM was near the optimum (NNI 0.85–1.03), but insufficient N nutrition (NNI 0.66–0.90) was common in PCM, GWC and CON plots.

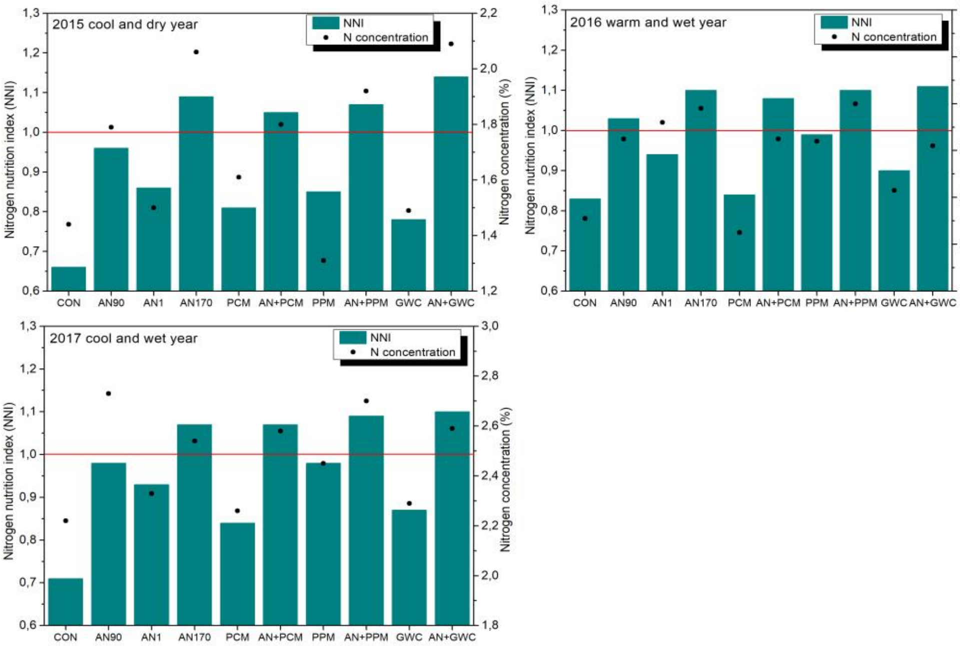

Figure 12. Nitrogen nutrition index (NNI) and maize N concentration (leaves + stalks) at the maize VT growth stage as affected by mineral and organic fertilisation.

Nitrogen uptake. At mid-season, N uptake differed significantly among treatments and years ($p < 0.01$), but a significant year x treatment interaction prevented me from pooling the three years' data (Fig. 13). Due to water shortage in 2015, N uptake was substantially lower, by 7.9–33.4% and by 11.5–39.4%, than in the wet years 2016 and 2017, respectively. The highest N uptake was observed in the plots AN170 (range 100.6–113.7 kg ha^{-1} N) and AN + PPM (range 85.3–110.9 kg ha^{-1} N). In contrast, the lowest N uptake and a substantial variation among years was typical of the plots GWC (range 51.3–84.6 kg ha^{-1} N) and CON (range 53.9–81.0 kg ha^{-1} N). These experimental outcomes are in line with previous findings of other authors who stated that in numerous crops, including maize, water limitation reduces N uptake (Pandey et al. 2000). However, these aforementioned N uptake differences among the years were possibly influenced not only by contrasting environmental conditions, but also by different amounts of readily plant-available soil N before maize sowing (*more details in part 2.1*).

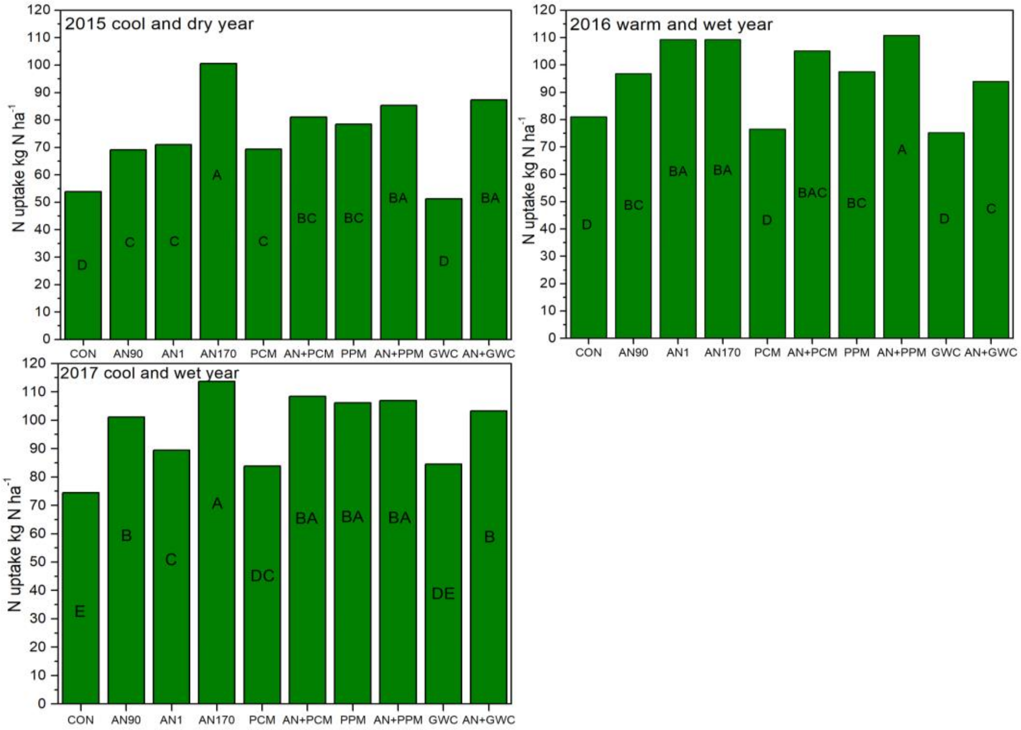

Figure 13. Maize nitrogen uptake at the VT growth stage as affected by mineral and organic fertilisation. Different combinations of letters indicate significantly different means (p < 0.05, Tukey's test).

Soil mineral N (N_{min}) content. Measurements of soil N_{min} content, which is an important indicator of readily available nitrogen, indicated significant differences ($p < 0.05$) between treatments in the upper soil layer (0–30 cm); however, N_{min} variation in the 31–60-cm soil layer was non-significant (Fig. 14). In all experimental years, differences among treatments were significant only in terms of nitrate (NO_3^--N), while there were no significant differences between treatments in terms of ammonium (NH_4^+-N). In 2015, the N_{min} content in the 0–30-cm soil layer ranged from 28.2 to 111.4 kg ha^{-1}, and the treatments were divided into four groups with the following decreasing order: AN + PCM ≈ AN + PPM ≈ AN90 > AN170 ≈ AN + GWC ≈ AN1 > PPM > PCM ≈ GWC ≈ CON. In the deeper soil layer, the differences were less pronounced, but in general, the treatments followed almost the same order as in the 0–30 cm layer. In 2016, the N_{min} content in the upper soil layer varied from 25.2 kg ha^{-1} in CON to 156.8 kg ha^{-1} in AN170. In the deeper soil layer (31–60 cm), the amount of N_{min} ranged from 35.9 to 69.3 kg ha^{-1}. In 2017, the N_{min} content in the 0–30-cm soil layer varied rather slightly from 23.7 to 81.8 kg ha^{-1}, while in the 31–60-cm soil layer, the amount of N_{min} ranged from 33 to 87.7 kg ha^{-1}, according for 51.7–61.1% of the total soil N at the depth of 0–60 cm. The difference among years can partly be explained by the higher initial soil N_{min}, most likely remaining from the previous year. In 2016, almost the 127.4 kg ha^{-1} of additional readily plant-available N (in 2015 – 95.6 and in 2017 – 65.7 kg ha^{-1} N) in the 0–60-cm soil layer could have substantially contributed to maize plant nutrition during the grain filling period. It should be noted that in all experimental years, NO_3-N accounted for most of the soil N.

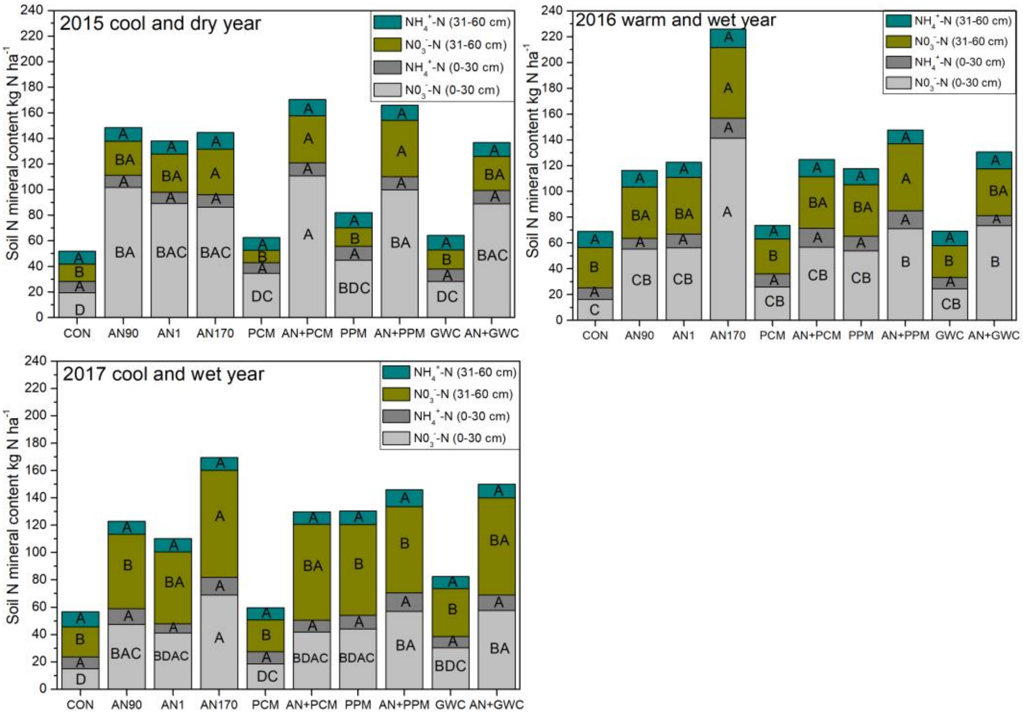

Figure 14. Soil mineral N (kg ha^{-1} N) concentrations at the VT growth stage of grain maize, 2015–2017. Different combinations of letters indicate significantly different means ($p < 0.05$, Tukey's test).

In summary, the grain maize vegetative period from sowing to tasselling was cool and particularly dry in 2015, warm and wet in 2016 and cool and wet in 2017. As a result, the measured plant traits and soil N status varied greatly between the experimental years. In the early growth stages, V5–V8, differences in TAB, LAI, SPAD and NNI between treatments were mostly small and non-significant. In all experimental treatments, NNI values (0.55–0.71) at the V8 growth stage indicated N deficiency, but Lemaire et al. (2008) stated that in the early plant growth stage, NNI values do not always adequately reflect the N status and do not consider variations in soil N supply. According to the TAB values, LAI measurements and other widely used criteria for determining plant and soil N status (SPAD, NNI, N concentration, nitrogen uptake, soil mineral N content), significant differences in the treatments were found already in July, at the end of the vegetative period (or mid-season). These differences stood out somewhat earlier in 2015.

As expected, the aforementioned plant and soil N indicators were closely related to each other. The correlation between SPAD values and NNI was significant, with similar R^2 values in 2017 (0.69) and 2015 (0.68) and slightly lower values in 2016 (0.48). The relationship between SPAD values and maize N uptake was higher in the wet years (R^2 = 0.84 in 2016 and 0.74 in 2017) than in the dry year 2015 (0.61). On the contrary, the correlation between SPAD values and Soil N_{min} (0–60 cm) was higher in 2015 with R^2 = 0.87 than in the wet years (R^2 = 0.49 in 2016 and 0.77 in 2017). Throughout the experimental period, a strong significant correlation was found between NNI and N uptake (R^2 = 0.75 in 2015, R^2 = 0.58 in 2016 and R^2 = 0.87 in 2017) as well as between NNI and Soil N_{min} (R^2 = 0.73 in 2015, R^2 = 0.61 in 2016 and R^2 = 0.88 in 2017) and among soil N_{min} and N uptake (R^2 - 0.48 in 2015, R^2 = 0.64 in 2016 and R^2 = 0.89 in 2017).

According to the NNI values from 2015–2017, maize N nutrition in AN170, AN + PCM, AN + PPM and AN + GWC was sufficient or even excessive (NNI > 1). In contrast, maize N nutrition in AN90, AN1 and PPM was below the optimum (NNI 0.85–0.99), while insufficient N nutrition (NNI 0.66–0.85) mostly occurred in PCM, GWC and CON. Measurements of N uptake and SPAD values have shown a similar lining up of treatments as observed for NNI. In combined treatments (AN + organic fertilisers,) maize nutrition at mid-season was sufficient; however, the soil N_{min} (0–60 cm) content in those treatments was also higher, especially in 2015, compared to that in plots receiving only organic fertiliser. These differences among the treatments resulted in significant differences in TAB and LAI.

3.5. The effects of different fertilisers on maize nutrition conditions and grain filling in the reproductive stage

The reproductive (R) stage of maize growth is characterised by the plant's ability to redirect resources from vegetative organs, i.e. leaves and stalks, to crop grain formation. At this growth stage, the vegetative organs are fully developed and do not grow anymore, while the kernels grow intensively; however, any stress in this stage, especially water stress, can substantially reduce grain yield. Maize reaches physiological maturity when a black layer appears at the bottom of the cob.

3.5.1. Maize growing period from tasselling to physiological maturity (growth stages: R1-R6)

Total above-ground biomass (TAB). At the milking stage (R3), the average accumulated TAB was 10.88 t ha^{-1} in 2015, 11.63 t ha^{-1} in 2016 and 10.05 t ha^{-1} in 2017. From 2015–2017, the effect of PPM on TAB was significant, with 24.7%, or 2.16 t ha^{-1} higher values than in the CON plots. In contrast, the effect of PCM was considerably lower: on average, TAB increased by only 11.2%, or 0.95 t ha^{-1}, compared to unfertilised plots (Fig. 15). In all experimental years, the impact of GWC was negligible, and the combination of organic and mineral fertilisers increased TAB by 26.7% in relation to CON; this effect was comparable to that observed in the plots with AN170 (28%).

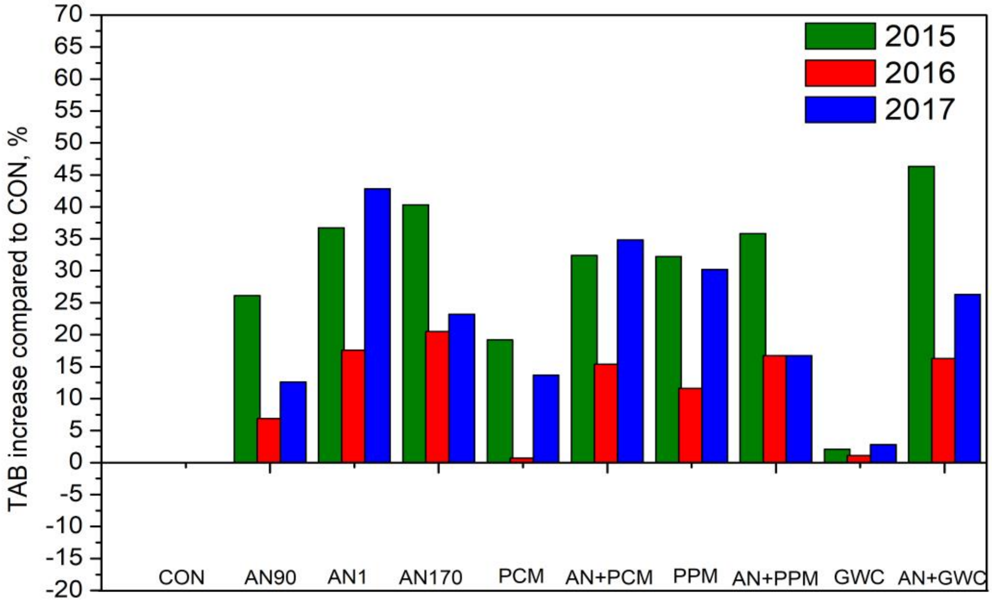

Figure 15. Total maize above-ground biomass accumulation at the milking (R3) growth stage in 2015–2017 as affected by mineral and organic fertilisation.

Leaf area index (LAI). At the milking stage (R3), significant differences in LAI among treatments were found in 2015 and 2017. On average, the highest LAI values were observed in the plots AN170 (2.48), AN1 (2.48) and GWC (2.47), while the CON plots had the lowest LAI (2.06). With the beginning of the reproductive phase, LAI continuously decreased, and at the R3 stage, the values were 17.2, 8.5 and 13.5 % lower in 2015, 2016 and 2017, respectively, than at mid-season. The differences in LAI among the different years are mostly attributed to the different temperature and water conditions during the growing seasons; at the stage R3, the LAI values of maize under drought stress (2015) were lower than those under adequate moisture conditions (2016 and 2017).

Chlorophyll meter (SPAD) readings. In 2015 and 2017, during the reproductive phase, the SPAD meter readings steadily decreased, while in 2016, there was no such evident decline (Table 15). In 2015, at the R2 growth stage, SPAD readings, on average, were 5.9% lower, while at the R3 stage, they were 16.6% lower than at mid-season. In 2017, at the stages R2 and R3, SPAD readings decreased only by 1.86 and 4.3%, respectively. It can be assumed that these differences were related to a reduced N uptake in the dry year 2015, because under water-limited conditions, leaf senescence and reallocation to the grains have been observed (Teixeira et al. 2014). Similar to the findings of Costa et al. (2001), the effects of fertilisers on SPAD readings was more pronounced as the plants aged. Despite the aforementioned peculiarities, in general, the highest SPAD readings during maize reproductive stages (R2 and R3) were observed for the AN170, AN + PPM and AN + GWC plots, while the lowest values were found in the GWC, PCM and CON plots.

Table 15. SPAD values of the youngest fully expanded maize leaf at the R2 and R3 growth stages in 2015−2017.

Treatment / year	R2 growth stage			R3 growth stage		
	2015	2016	2017	2015	2016	2017
CON	42.4 C	56.1 B	52.0 C	36.3 C	56.1 C	48.6 D
AN90	51.2 A	61.4 BA	60.8 A	47.1 A	61.4 BAC	58.2 A
AN1	51.6 A	63.1 BA	58.8 BA	44.8 BA	63.3 BA	56.6 BAC
AN170	52.9 A	62.2 BA	60.5 A	47.1 A	62.2 BAC	60.4 A
PCM	42.1 C	59.7 BA	52.6 C	37.4 C	57.8 BC	49.5 DC
AN + PCM	50.0 A	61.2 BA	60.5 A	43.6 BA	61.4 BAC	59.5 A
PPM	49.2 BA	62.8 BA	60.0 A	42.9 BA	64.2 BA	60.9 A
AN + PPM	52.3 A	62.9 BA	61.9 A	46.2 A	63.2 BA	60.3 A
GWC	43.5 C	58.4 BA	53.0 C	38.5 C	57.0 BC	52.9 BDC
AN + GWC	50.4 A	64.1 A	60.2 A	46.5 A	64.8 A	58.7 A

Note. R2 − maize blister stage, R3 – maize milking stage; different combinations of letters indicate significantly different means ($p < 0.05$, Tukey's test).

3.5.2. Maize yield, yield components and quality, nutrition and soil N status at harvest

Total above-ground biomass (TAB) and grain yield (GY). In October, at the stage of physiological maturity (R6), the harvested TAB ranged from 11.47 to 14.81 t ha^{-1} in 2015, from 13.67 to 19.04 t ha^{-1} in 2016 and from 12.58 to 16.49 t ha^{-1} in 2017 (Table 16).

Combined analyses of the three-year data showed significant differences among years and treatments, as well as a treatment x year interaction ($p < 0.01$). Generally, the treatments effects on TAB shoed the following order: AN170 ≈ AN + PCM ≈ AN + PPM ≈ AN + GWC > PPM ≈ AN1 ≈ AN90 > PCM ≈ GWC ≈ CON. In the cool-dry year 2015, the effects of PCM and GWC were non-significant (+0.29 and +0.15 t ha^{-1}, respectively, compared to the CON plots), while in the warm-wet year 2016, these effects were higher (+1.60 and +2.53 t ha^{-1}, respectively) than in the cool-wet year 2017 (+1.70 and 0.73 t ha^{-1}, respectively). Maize GY varied substantially among the different years, from 5.72 to 6.86 t ha^{-1} in 2015 over 6.94 to 9.56 t ha^{-1} in 2016 to 6.37 to 7.91 t ha^{-1} in 2017. Yields were higher by 34.5, 22.2, and 29.3 % than the actual yields reported by Lithuanian farmers for 2015, 2016 and 2017, respectively (Eurostat, 2018). Though combined analyses of the three-year data, similar to TAB, we observed significant differences among treatments for grain yield, but, in contrast to TAB, the year × treatment interaction was non-significant ($p = 0.19$ probability level). Despite some disparities, the effects of treatments on maize GY were the same those on TAB. Grain yield in the treatments with a combination of mineral and organic fertilisers was similar compared to the plots with AN170. However, the effects of organic fertilisers, without any additional mineral fertilisers, were contrasting: the average GY increase from the application of pelleted poultry manure was 93.7% of ammonium nitrate effect, while the increases from pelleted cattle manure and green waste compost were 32.9 and 23.8%, respectively.

Table 16. Total above-ground biomass (TAB) and grain yield (GY) (on a dry mass basis) for the years 2015−2017.

Treatments	TAB t ha^{-1}				GY t ha^{-1}			
	2015	2016	2017	average	2015	2016	2017	average
CON	11.47 B	13.67 D	12.58 E	12.57	5.72 B	6.94 C	6.37 C	6.34
AN90	13.87 A	16.60 BC	14.64 BDC	15.04	6.70 A	8.41 BAC	7.56 BA	7.56
AN1	14.21 A	17.51 BA	15.31BAC	15.68	6.66 A	8.74 BA	7.50 BA	7.63
AN170	14.53 A	18.52 A	15.49 BAC	16.18	6.85 A	9.02 BA	7.71 A	7.86
PCM	11.76 B	15.27 DC	14.28 EDC	13.77	5.77 B	7.78 BC	7.16 BAC	6.9
AN + PCM	14.30 A	17.60 BA	16.49 A	16.13	6.79 A	8.75 BA	7.88 A	7.81
PPM	13.68 A	17.53 BA	16.26 BA	15.82	6.55 A	8.85 BA	7.91 A	7.77
AN + PPM	14.81 A	17.76 BA	15.72 BAC	16.10	7.11 A	8.94 BA	7.88 A	7.98
GWC	11.62 B	16.20 BC	13.31 ED	13.71	5.72 B	7.82 BC	6.78 BC	6.77
AN + GWC	13.74 A	19.04 A	15.58 BAC	16.12	6.86 A	9.56 A	7.48 BC	7.97
Average	13.40	16.97	14.97		6.47	8.48	7.42	
Treatment		$p < 0.01$				$p < 0.01$		
Year		$p < 0.01$				$p < 0.01$		
Treatment × year interaction		$p < 0.01$				NS ($p < 0.19$)		

Note. Different combinations of letters indicate significantly different means ($p < 0.05$, Tukey’s test).

Yield components. The highest average grain number per cob (518) found in the warm-wet year 2016, while the corresponding values for 2015 and 2017 were approximately 10% lower (Table 17). Unexpectedly, the differences among the treatments were non-significant. The highest average 1,000-grain-weight was determined in 2016, while slightly lower values were found in 2017 and 2015. In all experimental years, grain yield was positively correlated with the 1,000-grain-weight ($R^2 = 0.85$ in 2015, $R^2 = 0.78$ in 2016 and R^2 0.77 in 2017), and this variation explained a major part of the maize grain yield variation.

Table 17. Responses of maize grain components to different N treatments.

Treatments	Grain number per cob				1,000-grain-weight			
	2015	2016	2017	average	2015	2016	2017	average
CON	449 A	527 A	431 A	469	261 BC	280 C	270 D	270
AN90	472 A	504 A	474 A	483	301 BA	314 BAC	307 BAC	307
AN1	463 A	514 A	478 A	485	303 A	309 BAC	301 BAC	304
AN170	462 A	524 A	488 A	491	311 A	316 BAC	312 BA	313
PCM170	486 A	524 A	472 A	494	245 C	294 BAC	284 DC	274
AN + PCM	486 A	523 A	483 A	497	292 BA	320 BA	294 BDC	302
PPM	470 A	522 A	478 A	490	294 BA	332 A	323 A	316
AN + PPM	477 A	515 A	464 A	485	306 A	314 BAC	313 BA	311
GWC	453 A	512 A	469 A	478	270 BAC	290 BC	283 DC	281
AN + GWC	462 A	511 A	477 A	483	302 BA	320 BA	296 BDC	306
Average	468	518	471		289	309	298	
Treatment	NS ($p < 0.12$)				$p < 0.01$			
Year	NS				NS			
Treatment × year interaction	NS				NS ($p < 0.15$)			

Note. Different combinations of letters indicate significantly different means ($p < 0.05$, Tukey's test); maize grain weight is expressed on a gram basis.

Yield quality. Maize grain protein concentration at harvest ranged from 5.4% to 8.5% in 2015, from 6.7% to 8.9% in 2016 and from 7.0% to 8.7 in 2017 (Table 18).

Table 18. Responses of maize protein and oil concentrations to different N treatments.

Treatments	Protein concentration %			Oil concentration %		
	2015	2016	2017	2015	2016	2017
CON	5.4 D	6.7 B	7.1 DC	4.2 A	4.0 A	4.0 A
AN90	7.3 B	8.1 A	8.4 BA	4.0 A	3.9 A	3.9 A
AN1	7.2 B	8.3 A	7.8 BDAC	4.0 A	4.1 A	4.0 A
AN170	8.5 A	8.9 A	8.4 BA	3.9 A	4.1 A	3.9 A
PCM	5.9 CD	7.0 B	7.0 D	4.1 A	4.1 A	4.1 A
AN + PCM	7.4 B	8.5 A	8.1 BAC	4.0 A	3.9 A	4.0 A
PPM	6.6 CB	8.5 A	8.3 BA	4.1 A	4.0 A	4.0 A
AN + PPM	7.4 B	8.7 A	8.7 A	4.0 A	4.0 A	3.9 A
GWC	5.9 CD	6.9 B	7.6 BDC	4.1 A	4.1 A	4.0 A
AN + GWC	7.4 B	8.1 A	8.4 BA	4.0 A	3.9 A	4.0 A
Average	6.9	8.0	8.0	4.0	4.0	4.0
Treatment	$p < 0.01$			NS		
Year	$p < 0.01$			NS		
Treatment × year interaction	$p < 0.01$			NS		

Note. Different combinations of letters indicate significantly different means ($p < 0.05$, Tukey's test).

Statistical analyses of the 2015–2017 data showed significant differences among years and treatments as well as treatment × year interaction ($p < 0.01$). The highest average protein concentration was determined for AN170 (8.6%), while the lowest values were found in the plots GWC (6.8%), PCM (6.6%) and CON (6.4%). It is likely that the low grain protein levels in the plots GWC, PCM and CON were the result of water stress and/or nutrient deficiencies during the vegetative phases. Besides, traditionally, it has been argued that the maize protein value is generally low due to the limited concentrations of the essential amino acids lysine and tryptophan (Mertz et al. 1964). It should be noted that the combined treatment (AN + organic fertilisers) increased the protein concentration from 0.5% to 1.4% compared to the treatment with organic fertilisers only. Throughout the experimental period, maize oil concentration varied slightly from 3.9–4.2%. In general, fertilisers of different origin and rate have no significant impacts on oil concentrations in plants, which is in agreement with the findings reported by Jellum et al. (1973), who observed that increasing N application rates had no influence on the oil concentration of maize grains.

Grain (HI), N (NHI), P (PHI) and K (KHI) harvest index. The harvest index (HI), which is the ratio between GY and TAB, is an important agronomic trait indicating the efficiency of dry matter allocation to the grain. In all experimental years, HI varied within a rather narrow range (Table 19); however, combined analysis of the three-year data showed significant differences among years ($p < 0.05$). On average, the HI was significantly lower in the cool-dry year 2015 (48.4%) than in the more favourable years 2016 (50.0%) and 2017 (49.7%). Nevertheless, the treatment and year × treatment effects were non-significant. For crops such as maize, the HI variation mostly depends on the genotype and the environmental condition and can range from 0.25 to 0.58 (Yang and Zhang, 2010). Although comprehensive experimental data in terms of HI variation are scarce for Lithuania, in comparison to the results of other studies, it can be stated that from 2015–2017, the variations in HI for grain maize were relatively high. The nutrient harvest index (nitrogen-NHI; phosphorus-PHI; potassium-KHI) is described as the ratio between respective nutrient uptake by the grain and uptake by the residual TAB. These indices reveal the re-translocation efficiencies of the absorbed nutrients from vegetative plant parts to the grains. In all experimental years, NHI, PHI and KHI varied between 55.8–70.8, 73.4–81.5 and 20.5–27.9, respectively (Table 19).

In this study, the NHI is of particular relevance because different types of fertilisers were compared and in this sense, the N translocation to the grain is an important indicator of fertiliser efficiency. On average, the NHI value was 63.5 in 2015, 65.1 in 2016 and 58.3 in 2017.

Table 19. Effects of different N treatments on maize grain harvest index (HI), nitrogen harvest index (NHI), phosphorus harvest index (PHI) and potassium harvest index (KHI) for the years 2015–2017.

Treatment	HI, %			NHI, %			PHI, %			KHI, %		
	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
CON	49.9 ± 0.4	50.8±0.6	50.6±0.9	66.1±3.5	66.1±0.5	57.9±2.1	78.5±2.1	74.2±1.7	75.1±1.8	26.9±2.0	26.2±0.8	24.6±2.1
AN90	48.3±0.9	50.7±1.1	51.6±0.8	62.1±3.4	64.9±2.0	56.7±1.9	81.1±2.2	74.5±2.0	78.7±1.9	27.2±0.4	24.9±2.7	21.7±1.8
AN1	46.9±1.1	49.9±0.6	49.0±1.3	66.5±0.1	65.7±2.3	56.3±1.6	78.6±0.2	76.2±3.7	74.9±2.6	27.9±0.9	26.3±2.2	22.1±1.6
AN170	47.1±0.5	48.7±1.5	49.8±1.4	65.9±0.6	63.8±0.4	55.8±0.9	80.5±0.2	76.7±1.7	79.2±1.6	24.8±0.2	26.1±1.6	20.5±1.5
PCM	49.1±0.7	50.9±1.2	50.1±1.7	60.9±2.3	65.4±2.1	61.7±2.0	74.8±2.6	73.5±1.5	73.7±1.9	25.2±1.8	27.1±2.1	20.7±1.7
AN + PCM	47.5±0.6	49.7±0.8	47.8±0.9	66.9±2.1	65.5±1.5	58.5±1.8	81.5±1.2	77.5±3.2	77.2±2.1	23.2±3.4	24.6±0.7	21.9±2.1
PPM170	47.9±1.2	50.5±1.3	48.6±0.9	60.1±0.1	61.9±0.7	58.1±0.9	76.7±2.1	75.3±0.3	77.2±0.8	26.4±0.1	24.7±2.4	21.7±1.6
AN + PPM	48.0±0.8	50.3±1.1	50.1±0.6	63.0±1.8	61.4±2.8	60.4±2.3	79.2±0.1	74.1±2.3	79.1±1.1	27.9±1.9	24.7±2.2	22.9±1.4
GWC	49.2±1.3	48.3±1.2	50.9±0.8	61.5±4.4	70.8±3.1	58.4±2.6	74.3±1.4	70.6±1.7	73.4±1.9	27.3±2.3	26.9±1.4	23.4±1.6
AN + GWC	49.9±1.1	50.2±1.6	48.0±1.2	61.6±2.2	65.7±2.7	59.0±2.5	79.6±0.3	77.0±1.3	76.7±1.2	25.6±2.2	24.1±0.1	20.8±0.9

Note. ± – standard error

These outcomes are consistent with the findings of Ciampitti and Vyn (2013), who investigated more than 100 data sources and determined that the average NHI of New-Era (1991–2011) maize hybrids is 63.4. The authors further suggest that although NHI values are conservative under non-limiting conditions, they can vary substantially due to unfavourable environmental conditions. In all experimental years, the variation in PHI values was not significant, but slightly higher values were observed in the dry year (78.5) than in the wet years (75 in 2016 and 76.5 in 2017). It is likely that unfavourable environmental conditions in 2015 triggered faster maize senescence, which resulted in an earlier phosphorus remobilisation to the developing grains and, consequently, in higher PHI values. Throughout the experimental period, the average PHI value in treatments was 76.7, which is somewhat higher than those measured in similar experiments in Central Poland (66.3) and North China (69) (Wu et al. 2015; Bak et al. 2016). Potassium is relatively mobile within the plant (Abendroth et al. 2011), and therefore, the parameter KHI can vary more significantly than NHI or PHI. In 2015 and 2016, the average KHI values were almost identical, i.e. 26.2 and 25.6, while in 2017, the value was slightly lower (22). Generally, in all years, the KHI values were somewhat lower than those indicated by other authors. For example, Bender et al. (2012) identified that for high-yielding maize hybrids, the average KHI was 0.33. Overall, in the combined treatments (AN with organic fertilisers), average NHI increased by 1–1.6% (except GWC) compared to the treatments with only organic fertilisers, while the NHI variation in the other treatments varied among different years without any clear tendencies. In the combined treatments, PHI was increased by more than 1.1–5.0% compared to the organic treatments. The different treatments had no significant impacts on KHI variation and tendencies.

Nitrogen uptake. At physiological maturity, the effects of year and treatment and the effects of year x treatment interaction on total maize N uptake were significant ($p < 0.01$). In general, N uptake correlated well with grain yield and was significantly lower in the cool-dry year 2015 than in the warm-wet year 2016 or the than cool-wet year 2017 (Fig. 16).

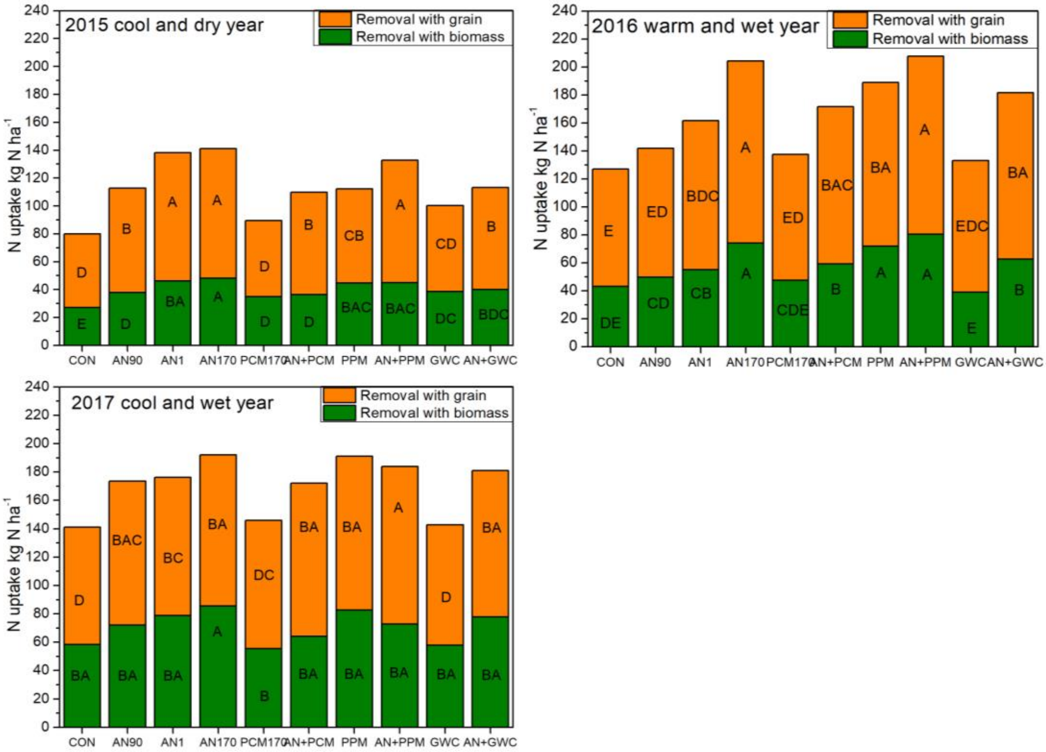

Figure 16. Nitrogen uptake at maize harvest as affected by mineral and organic fertilisation. Different combinations of letters indicate significantly different means ($p < 0.05$, Tukey's test).

Throughout the experimental period, maize N uptake behaviour differed with various environmental conditions. In 2015, from sowing to tasselling, maize accumulated 66.5% of the total N uptake, while in 2016 and 2017, the plants only accumulated 58.3% and 55.1%, respectively; these results are comparable to those reported by other authors (Girma et al. 2010). As expected, the highest total N uptake was determined in the plots AN170 (141.1–204.4 kg ha^{-1} N) and AN + PPM (132.7–207.8 kg ha^{-1} N), while the lowest values were found in CON (79.9–141.2 kg ha^{-1} N), PCM (89.5–145.9 kg ha^{-1} N) and GWC (100.2–142.8 kg ha^{-1} N). The relatively high values in the CON treatment are not surprising and are in agreement with those determined for winter wheat at this location (Lazauskas and Dabkevičius 1997). These authors found that N removal with winter wheat grain, depending on the cultivar and fungicide use can range between 68.0 and 90.8 kg ha^{-1} without fertilisation. However, the comparison of these two plants is rather arbitrary, because under non-limited growth conditions, maize has a higher biomass potential than temperate cereals such as wheat (Teixeira et al. 2014). Generally, the average N uptake increment from pelletised poultry manure application was 77% that from pelletised cattle manure 12.8% and that from green waste compost 14.8% compared with that of ammonium nitrate. These values are slightly higher than those reported by Muñoz et al. (2008).

Soil mineral N content (N_{min}). At maize harvest, substantial differences between treatments were found in terms of soil N_{min} in the upper soil layer (Fig. 17), while the differences among treatments in the deeper soil layer were non-significant. In the dry year 2015, nitrate-N accounted for 69.3% of N_{min} in the 0–60 cm soil layer, while the corresponding values for the wet years 2016 and 2017 were 52.6% and 55.39%, respectively. Furthermore, in comparison with the wet years, in 2015, the highest amount of nitrate-N (NO_3^--N) was accumulated in the 0–30-cm soil layer, which is most likely a result of the reduced N uptake and the restricted movement of N to deeper soil layers under the water deficit in 2015. In all experimental years, the highest soil N_{min} content was found in the plots supplied with AN170 and AN + PPM, whereas the lowest values were determined in the plots CON, PCM and GWC. The combination of mineral and organic fertilisers significantly increased total N_{min} contents, especially in 2015 (70.7–110.4%), compared to the plots with only organic fertilisers.

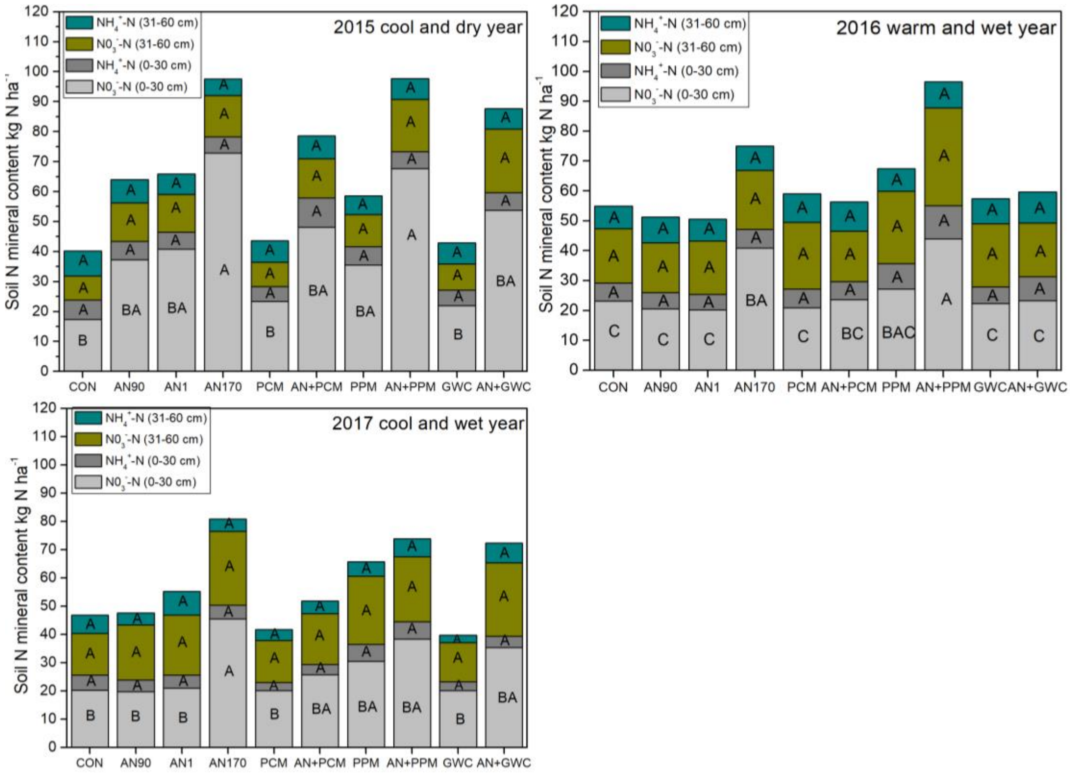

Figure 17. Soil mineral nitrogen (N_{min}) levels (kg ha^{-1} N) at maize harvest, 2015–2017. Different combinations of letters indicate significantly different means ($p < 0.05$, Tukey’s test).

3.6. The effects of different fertilisers on agronomic indices of nitrogen use efficiency

Indices of nitrogen use efficiency (NUE) are extremely useful for understanding the factors governing N uptake and fertiliser efficiency, comparing short-term fertilisation effects in different environments (Dobermann 2005). When comparing different years, among all treatments, the highest PFP_N index was determined in 2016 (60.9 kg grain kg^{-1} N), while it was slightly lower in 2017 (53.1 kg grain kg^{-1} N) and lowest in 2015 (46.3 kg grain kg^{-1} N) (Table 20). Throughout the experimental period, the highest PFP_N values were found for the plots AN90 (74.4–93.4 for 2015–2017) and AN1 (74–97.1 for the 2015–2017). All values in these treatments were higher than >70, which indicates high fertiliser efficiency. The values of this index decrease with increasing N application rates, and therefore, as expected, this index was significantly lower in all treatments supplied with N170. In all years, the lowest PFP_N values were found for the treatments PCM and GWC.

Table 20. Agronomic indices of nitrogen use efficiency for grain maize, 2015–2017.

Treatment	PFP_N (kg grain kg^{-1} N)			AE_N (kg grain kg^{-1} N)			RE_N (kg kg^{-1})		
	2015	2016	2017	2015	2016	2017	2015	2016	2016
CON									
AN90	74.4	93.4	84.0	10.9	16.3	13.2	0.36	0.17	0.36
AN1	74.0	97.1	83.3	10.4	20.0	12.6	0.65	0.39	0.39
AN170	40.3	53.1	45.4	6.6	12.2	7.9	0.36	0.46	0.30
PCM	33.9	45.8	42.1	0.3	4.9	4.6	0.06	0.06	0.03
AN + PCM	39.9	51.5	46.4	6.3	10.6	8.9	0.18	0.26	0.18
PPM	38.5	52.1	46.5	4.9	11.2	9.1	0.19	0.36	0.29
AN + PPM	41.8	52.6	46.4	8.2	11.8	8.9	0.31	0.48	0.25
GWC	33.6	46.0	39.9	0.0	5.2	2.4	0.12	0.04	0.01
AN + GWC	40.4	56.2	44.0	6.7	15.4	6.5	0.20	0.32	0.23

Note. PFP_N – partial factor productivity of applied N, AE_N – agronomic efficiency of applied N, RE_N – crop recovery efficiency of applied N

The AE_N value also varied greatly, with an average value of 6 (kg grain kg^{-1} N) in 2015, 12 (kg grain kg^{-1} N) in 2016 and 8.2 (kg grain kg^{-1} N) in 2017. Among treatments, the highest values were received in AN90 and AN1 and the lowest in GWC in PCM. The low values in the latter two treatments were probably a result of the absence of a significant grain yield increase.

Regarding the index RE_N, which depends on the congruence between plant N demand and the quantity of N released from applied N sources, the values varied between different years and were significantly lower compared to the values of PFP_N

and AE_N. The highest values were observed for the treatments AN1, AN170 and AN + PPM and the lowest for PCM and GWC. Basically, all the indices used in this study can be employed to estimate nitrogen use efficiency, but each of them has a specific limitation, making it rather difficult to claim which of the fertilisers was most effective. Contrasting conditions (temperature and water regime) during the experiments and different amounts of initial N concentrations also had a significant effect on the values of these indices. Therefore, these results should be carefully interpreted.

3.7. Relationships between the maize and soil N indicators grain yield, yield components and quality

The results of the correlation analysis of plant and soil traits for the different years are presented in Tables 21, 22 and 23. As shown in *Section 3.4.2*, in most cases, the relationships between SPAD values, plant N concentration, NNI, maize N uptake and Soil N_{min} (0–60 cm) at mid-season were significant. These results are not surprising, as these indicators directly or indirectly are related to nitrogen turnover in the plant and the soil. The more surprising correlation is that between the aforementioned N indicators and LAI. In the dry year 2015, there were no correlations between LAI and SPAD, N concentration, NNI, maize N uptake and N_{min} (0–60 cm); however, in the wet years (2016 and 2017), the correlations between LAI and most of these indicators were evident. This inconsistency between years may be due to the different environmental conditions, particularly in terms of water availability (*more details in section 3.1*).

Mid-season (growth stage VT) measurements of SPAD readings, NNI, maize N uptake and Soil N_{min} (0–60 cm) showed strong determination coefficients with final TAB and GY at physiological maturity. In 2015, SPAD values were strongly correlated with TAB ($R^2 = 0.95$, $p < 0.01$) and GY ($R^2 = 0.93$, $p < 0.01$), while in 2016 and 2017, correlation coefficients between SPAD and TAB were 0.60 and 0.71. A similar correlation was observed between SPAD and GY, varying between 0.62 and 0.69. Similar tendencies were observed when estimating the relationships between N_{min} (0–60 cm) and TAB and between N_{min} and GY. In the dry year, N_{min} (0–60 cm) was strongly correlated with final TAB ($R^2 = 0.84$, $p < 0.01$) and GY ($R^2 = 0.85$, $p < 0.01$), while in the wet years, these correlations were significantly lower. The NNI was strongly correlated with TAB ($R^2 = 0.66$, $p < 0.05$ in 2015; $R^2 = 0.77$ $p < 0.01$ in 2016 and $R^2 = 0.74$ $p < 0.05$ in 2017), and a similar correlation between NNI and GY was detected ($R^2 = 0.76$, $p < 0.05$ in 2015; $R^2 = 0.77$ $p < 0.01$ in 2016 and $R^2 = 0.76$ $p < 0.05$ in 2017). In 2015 and 2017, the relationships between N uptake and TAB and N uptake and GY were strong ($R^2 = 0.65$–0.82), while in 2016, this relationship was moderate ($R^2 = 0.51$–0.53).

A significant positive correlation between mid-season N indicators and GY components (1,000-grain-weight and grain number per cob) also was found. The correlations between SPAD and N_{min} (0–60 cm) with 1,000-grain-weight were highest in the dry year, with R^2 value of 0.88 and 0.69, respectively, while in the wet year, these correlations were significantly lower. On the contrary, the highest correlation between maize N uptake and 1,000-grain-weight was detected in the wet years ($R^2 = 0.51$, in 2016; $R^2 = 0.68$ $p < 0.05$ in 2017), while in the dry year, the correlation coefficient was only 0.49. In all experimental years, the correlation between NNI and 1,000-grain-weight was stable ($R^2 = 0.52–0.63$). Moderate correlations among NNI, maize N uptake, N_{min} (0–60 cm) and grain number per cob were detected only in 2017, while in other years, these correlations were relatively small. As expected, strong correlations were observed between all N indicators and the grain protein content.

Table 21. Correlation matrix for plant, soil traits, grain yield components and quality for 2015 for the growth stages VT and R6.

		VT growth stage						R6 growth stage								
		LAI	SPAD	N	NNI	NU	N_{min}	TAB	GY	HI	GNPC	GW	Protein	NHI	NU	N_{min}
VT growth stage	LAI		0.07	0.01	0.01	0.08	0.01	0.06	0.01	0.37	0.01	0.04	0.13	0.2	0.31	0.02
	SPAD	0.07		0.38	0.68*	0.61	0.87**	0.95**	0.93**	0.47	0.08	0.88**	0.88**	0.09	0.76*	0.75*
	N	0.01	0.38		0.79**	0.53	0.5	0.31	0.41	0.01	0.04	0.28	0.56	0.02	0.22	0.68*
	NNI	0.01	0.68*	0.79**		0.75*	0.73*	0.66*	0.78**	0.11	0.14	0.56	0.78**	0.01	0.43	0.87**
	NU	0.08	0.61	0.53	0.75*		0.48	0.65*	0.67*	0.25	0.14	0.49	0.77**	0.02	0.54	0.81**
	N_{min}	0.01	0.87**	0.5	0.73*	0.48		0.84**	0.85**	0.35	0.16	0.69*	0.77**	0.14	0.56	0.74*
R6 growth stage	TAB	0.06	0.95**	0.31	0.66*	0.65*	0.84**		0.96**	0.53	0.13	0.85**	0.82**	0.07	0.76*	0.78**
	GY	0.01	0.93**	0.41	0.76*	0.67*	0.85**	0.96**		0.33	0.11	0.85**	0.8**	0.04	0.66*	0.84**
	HI	0.37	0.47	0.01	0.11	0.25	0.35	0.53	0.33		0.12	0.36	0.43	0.18	0.61	0.22
	GNPC	0.01	0.08	0.04	0.14	0.14	0.16	0.13	0.11	0.12		0.66*	0.06	0.02	0.01	0.06
	GW	0.04	0.88**	0.28	0.56	0.49	0.69*	0.85**	0.85**	0.36	0.66*		0.78**	0.05	0.77**	0.69*
	Protein	0.13	0.88**	0.56	0.78**	0.77**	0.77**	0.82**	0.80**	0.43	0.06	0.78**		0.08	0.75*	0.83**
	NHI	0.2	0.09	0.02	0.01	0.02	0.14	0.07	0.04	0.18	0.02	0.05	0.08		0.07	0.07
	NU	0.31	0.76*	0.22	0.43	0.54	0.56	0.76*	0.66*	0.61	0.01	0.77**	0.75*	0.07		0.63*
	N_{min}	0.02	0.75*	0.68*	0.87**	0.81**	0.74*	0.78**	0.84**	0.22	0.06	0.69*	0.83**	0.07	0.63*	

Note. N – maize N concentration, N_{min} – soil N_{min} content at a depth of 0–60 cm, TAB – total above-ground biomass, GY – grain yield, HI – harvest index, GNPC – grain number per cob, GW – 1,000-grain-weight, protein – grain protein concentration, NHI– nitrogen harvest index, NU – N uptake

Table 22. Correlation matrix for plant, soil traits, grain yield components and quality for 2016 for the growth stages VT and R6.

		VT growth stage						R6 growth stage								
		LAI	SPAD	N	NNI	NU	N_{min}	TAB	GY	HI	GNPC	GW	Protein	NHI	NU	N_{min}
VT growth stage	LAI		0.24	0.61	0.33	0.4	0.53	0.26	0.18	0.33	0.08	0.14	0.41	0.06	0.32	0.25
	SPAD	0.24		0.74*	0.48	0.84**	0.49	0.6	0.62	0.02	0.01	0.67*	0.85**	0.29	0.51	0.05
	N	0.61	0.74*		0.72	0.88**	0.66*	0.69*	0.67*	0.07	0.11	0.59	0.89**	0.29	0.67*	0.22
	NNI	0.33	0.48	0.72*		0.58	0.61	0.77**	0.82**	0.05	0.09	0.63	0.74*	0.22	0.67*	0.23
	NU	0.4	0.84**	0.88**	0.58		0.64*	0.51	0.53	0.01	0.01	0.51	0.88**	0.42	0.63*	0.19
	N_{min}	0.53	0.49	0.66*	0.61	0.64*		0.56	0.51	0.12	0.01	0.38	0.72*	0.28	0.69*	0.27
R6 growth stage	TAB	0.26	0.6	0.69*	0.77**	0.51	0.56		0.97**	0.13	0.11	0.70*	0.71*	0.12	0.67*	0.13
	GY	0.18	0.62	0.67*	0.77**	0.53	0.51	0.97**		0.03	0.12	0.78**	0.74*	0.21	0.68*	0.13
	HI	0.33	0.02	0.07	0.05	0.01	0.12	0.13	0.03		0.01	0.01	0.02	0.23	0.03	0.01
	GNPC	0.08	0.01	0.11	0.09	0.01	0.01	0.11	0.12	0.01		0.04	0.02	0.04	0.01	0.02
	GW	0.14	0.67*	0.59	0.63*	0.51	0.38	0.70*	0.78**	0.01	0.04		0.78**	0.39	0.59	0.08
	Protein	0.41	0.85**	0.89**	0.74*	0.88**	0.72*	0.71*	0.74*	0.02	0.02	0.78**		0.47	0.78**	0.23
	NHI	0.06	0.29	0.29	0.22	0.42	0.28	0.12	0.21	0.23	0.04	0.39	0.47		0.51	0.4
	NU	0.32	0.51	0.67*	0.67*	0.63*	0.69*	0.67*	0.68*	0.03	0.01	0.59	0.78**	0.51		0.57
	N_{min}	0.25	0.05	0.22	0.23	0.19	0.27	0.13	0.13	0.01	0.02	0.08	0.23	0.4	0.57	

Note. Explanations under Table 21.

Table 23. Correlation matrix for plant, soil traits, grain yield components and quality for 2017 for the growth stages VT and R6.

		VT growth stage						R6 growth stage								
		LAI	SPAD	N	NNI	NU	N_{min}	TAB	GY	HI	GNPC	GW	Protein	NHI	NU	N_{min}
VT growth stage	LAI		0.57	0.22	0.53	0.59	0.61	0.62	0.47	0.58	0.29	0.25	0.32	0.07	0.59	0.59
	SPAD	0.57		0.66*	0.69*	0.74*	0.77**	0.71*	0.69*	0.27	0.24	0.59	0.80**	0.12	0.82	0.49
	N	0.22	0.66*		0.70*	0.68*	0.64*	0.4	0.54	0.01	0.19	0.43	0.81**	0.01	0.5	0.3
	NNI	0.53	0.69*	0.70*		0.87**	0.88**	0.74*	0.80**	0.25	0.52	0.52	0.81**	0.01	0.70*	0.54
	NU	0.59	0.73*	0.68*	0.87**		0.89**	0.75*	0.82*	0.19	0.51	0.68*	0.80**	0.05	0.80**	0.57
	N_{min}	0.61	0.77**	0.64	0.88**	0.89**		0.62	0.66*	0.17	0.42	0.63*	0.88**	0.12	0.86**	0.75*
R6 growth stage	TAB	0.62	0.71*	0.4	0.74*	0.75*	0.62		0.93**	0.51	0.57	0.6	0.53	0.01	0.74**	0.39
	GY	0.47	0.69*	0.54	0.76*	0.82**	0.66*	0.93**		0.25	0.58	0.77**	0.64	0.01	0.78**	0.39
	HI	0.58	0.27	0.01	0.25	0.19	0.17	0.51	0.25		0.19	0.05	0.06	0.01	0.22	0.17
	GNPC	0.29	0.24	0.19	0.52	0.51	0.42	0.57	0.58	0.19		0.39	0.27	0.04	0.4	0.13
	GW	0.25	0.59	0.43	0.52	0.68*	0.63*	0.6	0.77**	0.05	0.39		0.69*	0.07	0.84**	0.47
	Protein	0.32	0.80**	0.81**	0.81**	0.80**	0.88**	0.53	0.64*	0.06	0.27	0.69*		0.08	0.77**	0.56
	NHI	0.07	0.12	0.01	0.01	0.05	0.12	0.01	0.01	0.01	0.04	0.07	0.08		0.13	0.04
	NU	0.59	0.82**	0.5	0.70*	0.80**	0.86**	0.74*	0.78**	0.22	0.4	0.84**	0.77**	0.13		0.72*
	N_{min}	0.59	0.49	0.3	0.54	0.57	0.75**	0.39	0.39	0.17	0.13	0.47	0.56	0.04	0.72	

Note. Explanations under Table 21.

4. DISCUSSION

In this study, a relatively high maize grain yield was observed for the favourable environmental conditions in 2016 under unlimited N supply conditions (treatments AN170, AN + PCM, AN + PPM and AN + GWC), with an average of 10.43 t ha^{-1} (15% grain moisture) at the latitude 55°N in the Baltic region. This level of grain yield was approximately 3.49 t ha^{-1} higher than the average yield average yields reported by farmers. In general, the results of this specific year correspond to current global observations in the area, demonstrating that in poleward regions, the maize grain production becomes more feasible (Ramirez-Cabral et al. 2017). Hence, farmers in northern locations are encouraged to broaden the area of grain maize production. According to the results of this study, it can be assumed that in this Baltic area, even hybrids with a longer growing season should be considered. However, in other experimental years, the yield was significantly lower. For example, in the cool-dry year (2015), maize grain yield was 24% lower, while yield was 12% lower in the cool-wet year (2017) compared to the warm-wet year (2016). Substantial differences in maize yield among different growing seasons indicate the importance of gaining deeper insights into factors behind the year-to-year yield variation. Generally, in this study, year-to-year yield variation can be attributed mostly to contrasting environment conditions, namely temperature stress and water stress. This study highlighted that temperature stress during the vegetative maize growth stage is the dominant factor for yield potential losses. Low air temperatures (below 8°C) during the entire maize vegetation decreased yields from approximately 14.1% to 25.2%. Water stress during plant growth and development is another important phenomenon. Lithuania receives a surplus of water, where only 80% of precipitation evaporate and the rest run down to surface waters (Tumas 2003). However, the effect of a changing climate on the redistribution of rainfall among seasons is still unresolved (Rimkus et al. 2011), but it is obvious that in the future, it will be more difficult to avoid droughts because of the predicted global warming.

Interestingly, despite different environmental conditions, a strong correlation between mid-season NNI and grain yield traits was detected in this study (Fig. 18). The majority of plants are location- and season-specific, and therefore, it is important that a realistic yield goal is being set before sowing and that nutrients are applied in order to reach target yields (Roberts 2008). However, according to the results of this study, it is rather difficult to establish target yields for maize grain in the Baltic area as the temperature and water conditions substantially limit the potential yield, and it is even more difficult to predict future growing season temperatures and water availability variations.

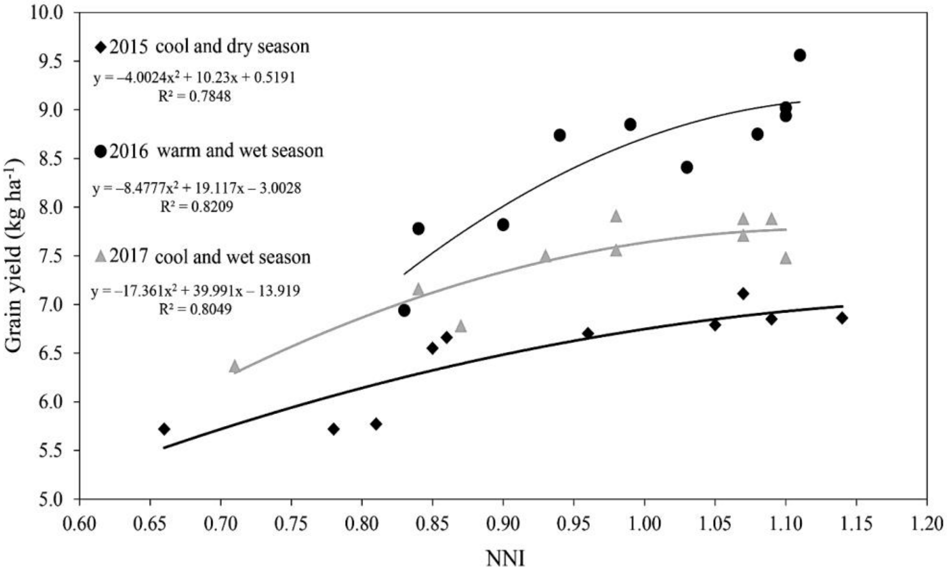

Figure 18. Relationship between maize grain yield and mid-season nitrogen nutrition index (NNI) for 2015–2017.

This study suggests that rate of 170 kg ha^{-1} N, in the form of ammonium nitrate, provides sufficient N under the specific soil and climatic conditions of the experimental site. However, from the environmental point of view, such a fertilisation rate can be too large because of the high amounts of nitrates in the soil after harvest in October. This study confirmed the findings of other authors that significant increases in nitrates can be expected when the mid-season calculated NNI was above 0.9 (Fig. 19).

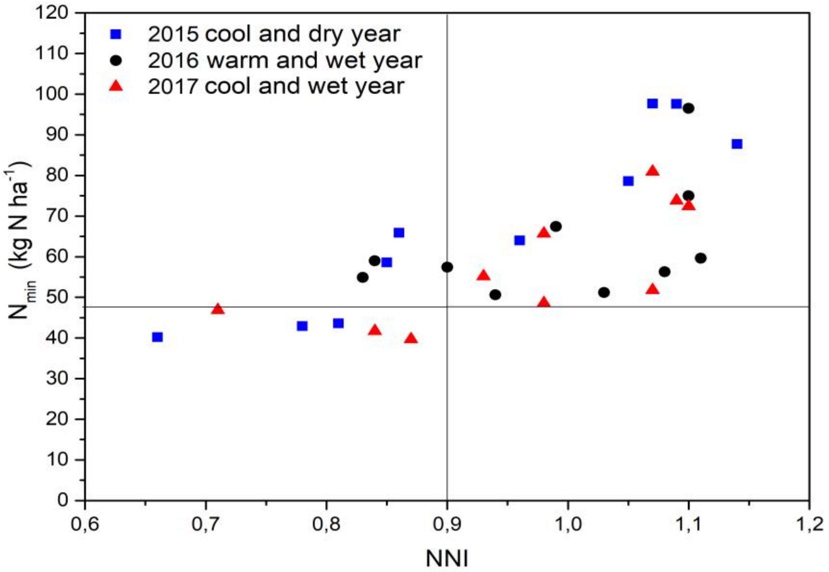

Figure 19. Relationship between mid-season nitrogen nutrition index (NNI) and soil mineral nitrogen (N_{min}) content after harvest at a depth of 0–60 cm.

It can be claimed that in the treatments AN170 and AN + PP M (where non-limited nitrogen nutrition of maize (NNI ≤ 1) was provided), the risk of nitrate leaching was the highest compared to the remaining experimental treatments. Excessive N fertilisation is often used by farmers for hedging; however, over-fertilisation can also occur due to an over-estimation of the target yield. For instance, a study in Finland indicated that fertilisation recommendations for spring crops, which are based on the expectations of farmers, can lead to crucial errors in N management practices (Valkama et al. 2013).

This study showed that N availability from pelleted cattle manure and green waste compost was lower than that from mineral fertilisers, while N availability from pelleted poultry manure was at the same level as that in mineral fertilisers. According to plant and soil N indicators (NNI, SPAD, soil N_{min} content), substantial differences among treatments were found already in July, at the end of the vegetative period. Additionally, it should be noted that mid-season values of SPAD, NNI, N uptake and soil N_{min} not only quantified plant and soil N status, but also well predicted the final yield of maize for grain and thus, farmers can use those N indicators. The findings of this study coincided well with those reported by Muñoz (2008), who confirmed that the effects of cattle manure on plant yields and N uptake were significantly lower than those of poultry manure. As expected, according to all N use efficiency indices, the most efficient treatments were those with lower fertilisation rates (N90). According to the N use efficiency index, there were no significant differences between combined treatments (AN + PCM, AN + PPM and AN + GWC) and treatments using mineral fertilisers (AN170). When comparing only organic fertilisers, pelleted poultry manure was the most efficient one, and its efficiency was close to that of the combined treatments. Thus, under Lithuanian environmental conditions, pelleted poultry manure can be considered an effective N source for grain maize, while green waste compost and pelleted cattle manure should be combined with mineral N fertilisers.

The main results of this study, related to the effects of mineral and organic fertilisers on grain maize growth and productivity, showed similar tendencies as in the studies of other authors. However, there are some other aspects that have not been investigated and comprehensively discussed. This study does neither indicate the amount of N losses to water and air nor amount of N preserved in the organic matter of the soil. Those issues have recently played a major role in the EU, where the aim is to effectively use N sources to meet plant requirements. However, all N sources have to be used in a sustainable and environmentally friendly way. For example, the EU Directive (2016/2284) obliges member states to reduce national emissions of certain atmospheric pollutants (sulphur dioxide, nitrogen oxides, non-methane volatile organic compounds, ammonia and fine particulate matter). Farmers also have to take into account the requirements of the Nitrate Directive of the EU (91/676/EEC), which limits manure application rates in nitrate-vulnerable zones (Schröder et al. 2013). Thus, future studies are needed not only to evaluate the N application efficiency in terms of crops productivity, but also to assess the impacts on the surrounding environment (e.g., water, air). The focus of this study was on the first-year maize performance; thus, the potentially positive effect of organic fertilisers in a long-term perspective was not investigated. Also, this study did not assess any potential other risk factors, such as heavy metal accumulation in soil and plants. However, it is important that before using different types of organic fertilisers, particularly green waste compost, such risks should be taken into account (Staugaitis et al. 2016).

CONCLUSIONS

1. The models AquaCrop and AgroC reproduced well experimental data of total above-ground biomass (RMSE = 0.54–1.33 t ha^{-1}; R^2 = 0.97–0.99), grain yield (RMSE = 0.35–1.01 t ha^{-1}; R^2 = 0.92–0.99), canopy cover (RMSE = 4.01–17.02 %; R^2 = 0.71–0.99) and soil water content (RMSE = 0.012 – 0.056 cm^3 cm^{-3}; R^2 = 0.41–0.78).
2. Under the climatic conditions of the experimental site, located in the nemoral zone, AgroC model predicted a fairly high potential grain yield of a short-season maize variety of 11.25–11.85 t ha^{-1}, while AquaCrop predicted 10.31–10.95 t ha^{-1}.
3. Grain yield reduction due to low temperatures simulated by AquaCrop model was 2.6 t ha^{-1} in 2015 and 1.54 t ha^{-1} in 2016, while for AgroC; the corresponding values were 2.39 t ha^{-1} and 1.9 t ha^{-1}, respectively. Losses due to water stress simulated by AquaCrop were 0.81 t ha^{-1} in 2015 and 0.48 t ha^{-1} in 2016, while AgroC predicted a larger loss of 1.93 in 2015 and 0.94 t ha^{-1} in 2016.
4. Pelleted poultry manure, applied at a rate of 170 kg of N, resulted in a grain yield similar to that achieved using ammonium nitrate. The effects of pelleted cattle manure and green waste compost on grain yield were rather small. The replacement of a portion of ammonium nitrate (N80) with organic fertilisers resulted in a similar maize grain yield, and no significant yield loss was recorded.
5. Mid-season measurements of the nitrogen nutrition index are a valuable tool for the ranking of treatments according to the maize N nutrition status. Ammonium nitrate or its combination with organic fertilisers (total 170 kg ha^{-1} N) provided sufficient maize N nutrition (NNI > 1). Pelleted poultry manure near optimum conditions (NNI 0.85–0.99), while insufficient N nutrition was common for pelleted cattle manure and green waste compost (NNI 0.78–0.90).
6. Mid-season measurements of soil N_{min} content provided the same ranking of treatments as nitrogen nutrition index. This ranking was the same as that for the final grain yield; therefore, mid-season indicators can be used to assess the maize N status and to predict maize grain yield.
7. The application of pelleted poultry manure before sowing can be considered as an effective N source for grain maize, while the application of pelleted cattle manure or green waste compost should be combined with mineral N sources.
8. The application of 170 kg ha^{-1} N as ammonium nitrate or pelleted poultry manure resulted in the highest yields, but also an increased accumulation of nitrate-N in the soil after maize harvest, indicating potential nitrate leaching.

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LIST OF PUBLICATIONS

Journals with impact factor in Clarivate Analytics Web of Science

1. **Żydelis R**, Lazauskas S, Povilaitis V. 2018. Biomass accumulation and N status in grain maize as affected by mineral and organic fertilisers in cool climate. Journal of Plant Nutrition (in press). doi.org/10.1080/01904167.2018.1527933
2. **Żydelis R**, Weihermüller L, Herbst M, Klosterhalfen A, Lazauskas S. 2018. A model study on the effect of water and cold stress on maize development under nemoral climate. Agricultural and Forest Meteorology 263:169–179. doi.org/10.1016/j.agrformet.2018.08.011

Conference reports

1. **Żydelis R**, Weihermüller L, Herbst M, Klosterhalfen A, Lazauskas S. Simulation of grain maize development under water and temperature stress: In: Book of Abstracts. 26th NJF Congress: Agriculture for the Next 100 Years, 27–29 June 2018, Kaunas distr., Lithuania, pp 28. Oral presentation.
2. **Żydelis R**, Lazauskas S. The effect of different organic fertilizers on grain maize under cool climate: In book of abstract. 17th International Ramiran Conference of Sustainable Utilisations of Manures and Residue Resources in Agriculture, 4–6 September, 2017, Wexford, Ireland, pp 70. Oral presentation.
3. **Żydelis R**, Lazauskas S. Maize response to different types of fertilizers in a droughty year: In: Book of Abstracts. 11th International Conference on Agrophysics: Soil, Plant and Climate, 26–28 September 2016, Lublin, Poland, pp 226. Poster presentation.
4. **Żydelis** R. Maize response to different fertilization. Conference: Novel methods for circulating plant nutrients – consequences for fertilizer value and soil fertility, 15–16 September 2016, Institute of Agriculture, Lithuanian Research Centre of Agriculture and Forestry. Oral presentation.
5. **Żydelis R**, Lazauskas S. The effect of organic fertilisers on maize growth for grain in Lithuania: In: Book of Abstracts. International Conference on Conservation Agriculture and Sustainable Land Use, 31 May – 2 June 2016, Budapest, Hungary, pp 104. Poster presentation.

ACKNOWLEDGEMENTS

First, I would like to thank my scientific supervisor Dr. Sigitas Lazauskas for the continuous support of my PhD study, for his patience, motivation, advice, ideas and suggestions. During the studies, we had many meetings where we discussed various topics, which helped me to improve not only as a scientist, but also as a human being, and for this, I will always be grateful. I would also like to thank all the technical staff of the Plant Nutrition and Agroecology Department for their cooperation in carrying out experimental measurements. I also wish to thank Dr. Jonas Volungevičius for a detailed description of the soil profile. My sincere thanks also go to the German Federal Environmental Foundation, which funded the internships (01/03/2017–06/08/2017) at the Agrosphere Institute IBG-3 at the Forschungszentrum Jülich, Germany. I would also like to thank the Director of the Agrosphere Institute, Prof. Dr. Harry Vereecken, who agreed to take me for the internship. Special thanks to my direct advisors during the internship, Dr. Lutz Weihermüller and Dr. Michael Herbst, who are absolute professionals in their field, and every discussion with them provided me with additional scientific knowledge. I am also grateful for my office friend in Germany, Anne Klosterhalfen, for help on a wide range of issues. I also thank Hongjuan Zhang for interesting discussions about science and other topics; you will always be an example for me how to work purposefully and to pursue your goal. I would also like to thank Kamilė for support. Finally, I wish to express my very profound gratitude to my parents for providing me with their unfailing support, love and continuous encouragement throughout my study years.

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SL 399. 2018.11.06. Sp. l. 12,1. Tiražas 15. Užsakymo Nr. 23. Leido ir spausdino
ASU Leidybos centras – 2018. Studentų g. 11, 53361 Akademija, Kauno r.