UNIWERSYTET
TECHNOLOGICZNO-PRZYRODNICZY
IM. JANA I JĘDRZEJA ŚNIADECKICH
W BYDGOSZCZY

WYDZIAŁ ROLNICTWA
I BIOTECHNOLOGII

ROZPRAWA DOKTORSKA

mgr inż. Krzysztof Bąk

OCENA STANU ODŻYWIENIA I POZIOMU PLONOWANIA KUKURYDZY (*Zea mays* L.) W WARUNKACH ZRÓŻNICOWANEGO NAWOŻENIA MINERALNEGO

PROMOTOR
DR HAB. RENATA GAJ

PROMOTOR POMOCNICZY
DR ANNA BUDKA

BYDGOSZCZ
2016

Promotor
Pani dr hab. Renacie Gaj
za rady, cenne uwagi, okazane
wsparcie oraz
szczególną życzliwość,
składam serdeczne wyrazy
podziękowania

Serdeczne podziękowania
Pani dr Annie Budce
za okazaną pomoc statystyczną
przy realizacji pracy

Spis treści

1. WYKAZ ORYGINALNYCH PRAC TWÓRCZYCH STANOWIĄCYCH ROZPRAWĘ DOKTORSKĄ

A -1

Bąk K., Gaj R. 2016. The effect of differentiated phosphorus and potassium fertilization on maize grain yield and plant nutritional status at the critical growth stage. J. Elem. 21(2): 337-348 10.5601/jelem.2015.20.3.996

15 pkt. wg MNiSW, If= 0,719

A –2

Bąk K, Gaj R., Budka A. 2016. Accumulation of nitrogen, phosphorus and potassium in mature maize under variable rates of mineral fertilization. Fragm Agron 33(1): 7-19**.** **12 pkt. wg MNiSW**

A –3

Gaj R**., Bąk K.,** Budka A. 2016. Acquisition of copper and manganese by maize (*ZEA MAYS* L) grown under differentiated mineral fertilization with P and K. Biometrical Letters. V 53(1): 21-36. **12 pkt. wg MNiSW**

A – 4

Bąk K., Gaj R**.,** Budka A. 2016. Zinc distribution in maize under differentiated rates of mineral fertilization with phosphorus and potassium. J.Elem. 21(4): 989-999 DOI 10601/jelem.2015.20.3.1095

15 pkt. wg MNiSW, If= 0,719

2. WSTĘP

Kukurydza jest rośliną, która w ostatnim 10-leciu wykazuje dużą dynamikę wzrostu powierzchni uprawy w Polsce, a także w innych krajach europejskich. Zainteresowanie uprawą tej rośliny w naszym kraju systematycznie wzrasta i wynika z jednej strony z wszechstronności jej użytkowania, a z drugiej strony ze względów ekonomicznych spowodowanych wzrostem wydajności. Uzyskanie pozytywnego wyniku ekonomicznego jest możliwe tylko w oparciu o dokładnie opracowaną agrotechnikę, która uwzględnia kontrolę stanu odżywienia roślin oraz definiuje czynnik lub grupę czynników odpowiedzialnych za plonowanie kukurydzy. Niezbędnym elementem wiedzy dla prawidłowego ustalenia planu nawożenia kukurydzy jest znajomość aktualnej zasobności gleby, jednostkowego pobrania składników oraz poprawne oszacowanie wielkości spodziewanego plonu w danym stanowisku. W literaturze przedmiotu mało jest dostępnej wiedzy dotyczącej krytycznej zawartości składników w glebie, które z jednej strony informują o konieczności nawożenia fosforem (P) i potasem (K), a z drugiej strony gwarantują uzyskanie maksymalnych plonów. Plon ziarna kukurydzy odzwierciedla stan niezbilansowana składników w okresie wegetacji roślin. Ryzyko spadku plonu można zmniejszyć stosując zbilansowane nawożenie mineralne w odniesieniu do wszystkich składników pokarmowych. Kukurydza spośród uprawianych zbóż posiada największy potencjał plonotwórczy, którego podstawowym warunkiem realizacji jest stanowisko bogate we wszystkie składniki mineralne. Roślina ta wykazuje dużą wrażliwość i zmienność na zaopatrzenie w składniki pokarmowe w okresie wegetacji. Niedobór składników pokarmowych w fazie szybkiego wzrostu biomasy wywołuje liczne zakłócenia w procesach formowania struktury kolby, co ma kluczowe znaczenie dla końcowego plonu. Dane literaturowe wskazują, że w fazie tuż przed i po kwitnieniu (okres około 3 tygodni) niedobór wody, potasu i boru stanowi o stopniu uziarnienia kolby, a w konsekwencji o końcowym plonie ziarna. Szczególne znaczenie odgrywają początkowe fazy wzrostu tej rośliny tj. do wykształcenia 8-go liścia. W tym stadium rozwoju, kukurydza wykazuje bardzo dużą wrażliwość na niedobór fosforu, którego pobieranie w bardzo dużym stopniu zależy zarówno od stężenia jonów ortofosforanowych w roztworze glebowym, temperatury oraz odżywienia innymi składnikami mineralnymi.

W kontekście nawożenia fosforem pojawia się problem niskiego wykorzystania składnika z nawozów, którego konsekwencje ujawniają się w postaci eutrofizacji wód. Liczne badania wskazują, że 50-80% aplikowanego fosforu w formie nawozów jest adsorbowana przez glebę i jak dotąd nadal brakuje informacji o dawce nawozowej P, która zapewni wystarczający poziom dostępnego składnika dla roślin, nie powodując jednocześnie spadku plonu.

Drugim składnikiem krytycznym w uprawie kukurydzy jest potas, którego niedobór w glebach od wielu lat stanowi światowy problem. Składnik ten jest żywieniowym czynnikiem kontroli gospodarki wodnej w roślinie. W Europie ponad 25% gleb wykazuje niską zawartość K przyswajalnego, natomiast w Polsce ostanie badania przeprowadzone przez Stację Chemiczno-Rolniczą w Warszawie pokazują, że gleby o bardzo niskiej i niskiej zasobności stanowią ponad 40%. Potas w najbliższej perspektywie będzie obok wody głównym czynnikiem wpływającym na brak stabilności plonowania kukurydzy, a także innych gatunków roślin uprawnych.

3. PROBLEM BADAWCZY I CEL BADAŃ

Aktualny stan wiedzy w zakresie reakcji kukurydzy na zaopatrzenie w fosfor i potas pozwala sformułować następujący problem badawczy: czy *stosowanie zróżnicowanego nawożenia mineralnego fosforem i potasem ma istotny wpływ na stan odżywienia kukurydzy w fazach krytycznych, kształtowanie wielkości plonu oraz zawartość i akumulację składników w fazie dojrzałości fizjologicznej?*.

CEL BADAŃ

Celem badań była ocena stanu odżywienia kukurydzy w fazach krytycznych (BBCH 17, BBCH 65) oraz wielkości plonu rozważana w aspekcie dawki optymalnej składników mineralnych aplikowanych w nawozach oraz zredukowanego poziomu nawożenia fosforem i potasem.

W celu rozwiązania postawionego problemu badawczego sformułowano następujące pytania szczegółowe:

1. Czy istnieje zależność pomiędzy stanem odżywienia kukurydzy w fazach krytycznych (przypadających na fazę 7-8 w pełni rozwiniętych liści oraz początek kwitnienia), a plonem ziarna kukurydzy w warunkach zróżnicowanego nawożenia mineralnego fosforem i potasem?
2. Czy zróżnicowane nawożenie mineralne P i K wpływa na gospodarkę makro i mikroskładników w roślinie w okresie wegetacji?
3. Czy kukurydza wykazuje rekcję plonotwórczą i żywieniową na formę fosforu aplikowaną w nawozie mineralnym?
4. Jak należy gospodarować fosforem i potasem w glebach o średniej zasobności w fosfor i potas przyswajalny, w warunkach intensywnej produkcji, uproszczonego zmianowania, aby uzyskać stabilny plony ziarna kukurydzy?

4. METODYKA BADAŃ

Badania przeprowadzono w latach 2007-2011 w gospodarstwie rolnym w Wieszczyczynie k. Śremu 52º02' N 17º05'E. Podstawą badań było jednoczynnikowe doświadczenie z kukurydzą odmiany *Veritis* (FAO: 230-240). Doświadczenie stanowiło kontynuację wieloletniego eksperymentu założonego w 2000 roku, metodą bloków losowanych kompletnych w czterech powtórzeniach. Czynnikiem doświadczalnym był zróżnicowany poziom nawożenia mineralnego fosforem i potasem.

Podstawą do wyznaczenia dawek nawozowych N, P, K, Mg była aktualna ocena zasobność gleby, pobranie jednostkowe składników oraz spodziewany plon. W każdym roku wyznaczono optymalny poziom nawożenia mineralnego oznaczany jako W100. Analizie poddano 8 następujących wariantów, które różniły się poziomem nawożenia fosforem i potasem: kontrola absolutna, brak w nawożeniu jednego z głównych składników (P - WPN lub K - WKN), zredukowane dawki fosforu i potasu odpowiednio do 25 i 50% względem wariantu optymalnie nawożonego (25% - W25 oraz 50% WP50, WK50) oraz dodatkowo wprowadzono wariant, w którym jako alternatywne źródło fosforu dla superfosfatu pojedynczego zastosowano częściowo zakwaszony fosforyt (PAPR) - W100 PAPR. W badaniach wykorzystano fosforyt o zawartości P ogólnego 10,2% P i zakwaszeniu 50% (tzn., że ilość kwasu siarkowego zużyta w procesie technologicznym do otrzymania produktu stanowiła 50% ilości koniecznej do produkcji superfosfatu pojedynczego). Zalecany poziom nawożenia mineralnego kukurydzy w latach badań (2007/2008/2009/2010/2011) przedstawiał się następująco: kg $N \cdot ha^{-1}$ 120/120/150/150/150; 35/26/26/26/26 kg $P \cdot ha^{-1}$; 100/125/133/125/125 $K \cdot ha^{-1}$ i 16 kg $Mg \cdot ha^{-1}$. Fosfor, potas i magnez aplikowano jednorazowo jesienią, natomiast azot stosowano w dwóch dawkach, 70% przed siewem kukurydzy i 30% w fazie 4 wykształconych liści kukurydzy. Przedplonem kukurydzy w każdym roku badań była pszenica ozima. Podstawowe informacje o warunkach glebowych, meteorologicznych oraz plonie ziarna kukurydzy zawiera praca A-1.

Rośliny do analiz chemicznych pobrano ze wszystkich poletek w trzech terminach przypadających na następujące fazy rozwojowe: (1) 7-8 wykształconych liści (BBCH 17); (2) kwitnienie (BBCH65) (3) dojrzałość fizjologiczna (BBCH 89). W pierwszym terminie z każdego poletka losowo pobrano po 10 roślin. W drugim etapie analizie poddano tylko liść podkolbowy kukurydzy, natomiast w fazie dojrzałości fizjologicznej analizę składników mineralnych przeprowadzono w poszczególnych organach rośliny tj.: liście, łodygi, kolby, rdzenie, liście okrywowe, ziarno. Plon ziarna oraz biomasy słomy określono zbierając rośliny ręcznie z powierzchni 24 m^2 . W losowo wybranych 5 kolbach z każdego wariantu oznaczono masę tysiąca ziaren.

Materiał roślinny w celu określenia zawartości analizowanych składników mineralizowano na sucho w 640°C, a następnie popiół rozpuszczano w 33% HNO_3. Analizę zawartości składników mineralnych przeprowadzono metodami standardowymi (N metodą Kjeldahla, P kolorymetrycznie, K i Ca metodą fotopłomieniową oraz Mg, Zn, Cu, Mn Fe metodą adsorpcji atomowej ASA.

4.1. Analiza statystyczna wyników

Do analizy wyników plonu ziarna kukurydzy oraz zawartości składników w materiale roślinnym zastosowano dwuczynnikową analizę wariancji, w której czynnikami doświadczalnymi były: rok oraz zróżnicowany poziom nawożenia mineralnego fosforem i potasem. Dla porównania średnich zawartości makro i mikroskładników dla poszczególnych wariantów nawożenia mineralnego zastosowano procedurę Tukey'a porównań wielokrotnych w celu podzielenia zbioru średnich na grupy jednorodne. Dla oszacowania związków przyczynowo-skutkowych między analizowanymi parametrami zastosowano analizę regresji wielokrotnej. W celu skonstruowania modelu regresji wykorzystano metodę krokową mieszaną, w której algorytm zarówno dodaje, jak i usuwa zmienne w kolejnych krokach minimalnego zestawu zmiennych niezależnych przy jednoczesnej maksymalizacji współczynnika determinacji i minimalizacji średniego kwadratu odchyleń od modelu regresji.. W wyniku przeprowadzonej regresji wyodrębniono zmienne decydujące o wielkości uzyskanych plonów. Konsekwencją tego, że zmienne niezależne są skorelowane jest brak możliwości określenia w jednym kroku zestawu tych zmiennych niezależnych, które powinny pozostać w modelu funkcji regresji. Oznacza to konieczność wypracowania innej metody pozwalającej na określenie najlepszego zestawu zmiennych niezależnych.

Analiza Składowych Głównych (PCA) posłużyła do wykazania prawidłowości (oddzielnie dla każdego wariantu) zachodzących między zmiennymi: plon ziarna kukurydzy, zawartość składników w analizowanych organach oraz pobranie pierwiastków.

Ocenę wpływu zmiennego nawożenia P i K na zawartość składników w analizowanych organach w fazie dojrzałości fizjologicznej kukurydzy przedstawiono graficznie za pomocą map ciepła.

5. SYNTETYCZNE OMÓWIENIE WYNIKÓW PRAC STANOWIĄCYCH PRZEDMIOT ROZPRAWY DOKTORSKIEJ

Uzyskane rezultaty badań zostały przedstawione w 4 oryginalnych pracach twórczych zgodnie z numeracją zamieszczoną w wykazie:A-1, A-2, A-3, A-4 i dodatkowo uzupełnione o wyniki otrzymane w przeprowadzonym eksperymencie, które nie zostały ujęte w opublikowanych pracach. Zaprezentowane wyniki badań stanowią odpowiedź na postawiony problemy badawczy i pytania szczegółowe sformułowane przed rozpoczęciem eksperymentu polowego.

5.1. Stan odżywienia kukurydzy w fazach krytycznych

Ocenę stanu odżywienia roślin przeprowadzono w dwóch terminach, przypadających na stadium 7-8 rozwiniętych liści kukurydzy oraz kwitnienie (A-1, A-3, A-4). Oznaczono zawartość makro i mikroskładników w liściach i oceniono w oparciu o zakresy standardowe wyznaczone przez SCHULTE I KELLING (2000). Ocena zawartości składników we wczesnej fazie rozwoju kukurydzy ma duże znaczenie utylitarne, ponieważ w przypadku stwierdzenia niedostatecznego zaopatrzenia roślin w składniki mineralne, istnieje możliwość przeprowadzenia korekty nawozowej. W pracy A-1 uwzględniono pierwszą fazę krytyczną, natomiast w pracach A-3 i A-4 analizie poddano ocenę wpływ zróżnicowanego nawożenia mineralnego fosforem i potasem na zawartość mikroskładników w fazie kwitnienia kukurydzy.

Stan odżywienia roślin w fazie 7-8 rozwiniętych liści przeprowadzono na podstawie średnich zawartości składników z lat 2007-2011. Zróżnicowane dawki P i K, nie miały istotnego wpływu na zawartość azotu, fosforu, potasu, wapnia, magnezu i żelaza. Czynnik doświadczalny różnicował jedynie koncentrację miedzi i manganu w liściach kukurydzy (praca A-3). Wykazano, że niezależnie od analizowanego wariantu rośliny były niedożywione zarówno makro jak i mikroskładnikami. Szczególnie niskie zawartości zanotowano w przypadku wapnia i magnezu, których poziomy zawartości kształtowały się znacznie poniżej dolnej wartości granicznej. Wyjątek stanowiło jedynie żelazo, którego zawartość kształtowała się powyżej dolnego przedziału wartości normatywnej. *Forma zastosowanego fosforu w nawozie mineralnym w porównaniu do wariantu nawożonego superfosfatem również nie powodowała istotnych różnic ani w zawartości fosforu, ani w koncentracji pozostałych ocenianych składników w liściach.*

W drugiej analizowanej fazie krytycznej przypadającej na stadium kwitnienia roślin wykazano, że zawartość azotu, fosforu, magnezu, cynku i miedzi podobnie jak w pierwszym ocenianym terminie, przedstawiała się poniżej wartości optymalnych wyznaczonych przez (SCHULTE, KELLING 2000). Prawidłowy stan odżywienia kukurydzy odnotowano w przypadku potasu, wapnia i manganu. Niezależnie od roku badań czynnik doświadczalny nie miał wpływu na zawartość potasu. Istotne różnice w zawartości tego składnika stwierdzono jedynie w porównaniu do obiektu kontrolnego. Zróżnicowane nawożenie mineralne P i K w znacznie większym stopniu różnicowało zawartość Mg i Ca w liściu podkolbowym kukurydzy niż w początkowym stadium wzrostu. Rośliny wykazały stan luksusowego zaopatrzenia w wapń niezależnie od badanego obiektu, natomiast zawartość magnezu kształtowała się poniżej wartości granicznej. Kukurydza w warunkach doświadczalnych, czyli przy założonym niedoborze P lub K w nawożeniu wykazała, że niedobór szczególnie potasu zwiększał zawartość wapnia i magnezu w roślinie. Brak potasu w nawożeniu spowodował zmniejszoną zawartość składnika (K) w organach wskaźnikowych z jednoczesną kompensacją wapnia i magnezu. Niedobór potasu w liściach wywołał wzrost zawartości magnezu w obydwu analizowanych terminach Największą zawartość analizowanych składników (Ca i Mg) w liściach kukurydzy odnotowano w wariancie, na którym od 10 lat nie stosowano potasu, co jednoznacznie wskazuje na antagonistyczną relację między tymi pierwiastkami. Brak potasu w nawożeniu spowodował zmniejszoną zawartość składnika w organach wskaźnikowych z jednoczesną kompensacją wapnia i magnezu. *Forma chemiczna fosforu analogicznie jak w pierwszym terminie nie miała istotnego wpływu na zawartość ocenianych składników w liściach kukurydzy w fazie kwitnienia.*

Ze względu na duży stopień wrażliwości kukurydzy względem cynku, mikroskładnik ten został omówiony w oddzielnej pracy A-4. W tej publikacji skoncentrowano się na wskazaniu wpływu zróżnicowanego nawożenia mineralnego na gospodarkę cynkiem zarówno w fazach krytycznych jak również w fazie dojrzałości fizjologicznej kukurydzy. Szczególną uwagę zwrócono na aspekt zależności pomiędzy fosforem a zawartością cynku w roślinie, ze względu na antagonistyczne działanie pomiędzy pierwiastkami. W przeprowadzonych badaniach, w początkowej fazie wzrostu, niezależnie od analizowanego wariantu relacja P/Zn kształtowała się w zakresie 91,34-122,9 co w konfrontacji z danymi literaturowymi wskazuje na optymalne odżywienie cynkiem. Stan odżywienia cynkiem oraz innymi składnikami w fazie kwitnienia jest jednym z najważniejszych okresów w rozwoju kukurydzy, który ma istotny wpływ na kształtowanie ostatecznego plonu tej rośliny. W porównaniu do fazy BBCH17 zawartość Zn w analizowanych organach w fazie kwitnienia była niższa.

Niezależnie od analizowanego wariantu, koncentracja Zn w liściu podkolbowym kształtowała się znacznie poniżej wartości normatywnych (19-75 ppm). Istotne różnice w zawartości cynku stwierdzono zarówno w porównaniu do obiektu kontrolnego jak również pomiędzy obiektami nawożonymi. Zmniejszenie dawki potasu do 50%, bądź też pominięcie tego składnika w nawożeniu skutkowało większą redukcją zawartości cynku w liściach kukurydzy niż w przypadku analogicznych obiektów z fosforem. Czynnikiem różnicującym zawartość cynku w liściach kukurydzy w fazie kwitnienia były również niekorzystne warunki pogodowe, które w sposób szczególny zaznaczyły się przed kwitnieniem kukurydzy w latach 2008 i 2009. Niedobory wody w tym okresie skutkowały niższą zawartością składnika w liściach. W fazie dojrzałości fizjologicznej czynnik doświadczalny również istotnie różnicował zawartość cynku w analizowanych organach.

5.2. Zależność pomiędzy plonem ziarna kukurydzy a stanem odżywienia roślin

Ocenę stanu odżywienia roślin w trakcie wegetacji wykonuje się w celu zdiagnozowania aktualnego stanu zaopatrzenia roślin w składniki mineralne oraz prognozowania plonu końcowego. Wartość prognostyczna wzrasta w sytuacji odniesienia zawartości składników do aktualnej ich zawartości w roślinie.

Przeprowadzona w badaniach własnych ocena stanu odżywienia kukurydzy w wyznaczonych fazach krytycznych wykazała wysoce istotną zależność pomiędzy zawartością składników mineralnych w analizowanych organach a plonem ziarna. Powyższa zależność została opisana za pomocą równań regresji wyznaczonych oddzielnie dla każdego analizowanego wariantu, i fazy krytycznej. W fazie BBCH 17, wartości współczynników determinacji kształtowały się w zakresie od 59% do 94% (praca A–1), co wskazuje na silną zależność plonu od odżywienia roślin. Wykazane zależności informują, że im bardziej zakłócona jest homeostaza żywieniowa, tym rola analizowanych składników w kształtowaniu plonu jest większa.

Analiza korelacji pomiędzy zawartością składników w liściu podflagowym w fazie kwitnienia a plonem ziarna kukurydzy przeprowadzona oddzielnie dla każdego obiektu, wykazała istotne zależności dla większości analizowanych składników. Szczególnie wysokie współczynniki korelacji uzyskano dla azotu ($r = 0,78$) i fosforu ($r = 0,53$). W przypadku kluczowego mikroskładnika, jakim jest cynk, silniejszą zależność plonu ziarna kukurydzy od stanu odżywienia roślin cynkiem, stwierdzono w fazie kwitnienia (BBCH65) niż fazie początkowego wzrostu tj BBCH17, co potwierdzają wyższe wartości współczynników korelacji (tabela 1).

Tabela 1. Współczynniki korelacji pomiędzy plonem ziarna kukurydzy a zawartością cynku w fazach krytycznych

Faza rozwojowa	Warianty nawożenia/Treatments							
	Control	WPN	WKN	W25	WP50	WK50	W100	W100 P as PAPR
	Współczynniki korelacji / Correlation coefficients							
Zawartość cynku BBCH 17	-0,03	0,18	-0,10	0,59*	0,33	0,21	0,30	0,38
Zawartość cynku BBCH 65	0,13	0,769*	0,62*	0,40	0,38	0,67*	0,39	0,37

*p<0,05

Analiza regresji przeprowadzona metodą wsteczną krokową dla drugiej ocenianej fazy krytycznej, również dowiodła istotną zależność plonu ziarna kukurydzy od stanu odżywienia roślin w fazie kwitnienia. Wartości współczynników determinacji w wyznaczonych równaniach regresji kształtowały się w zakresie od 74 do 94%.

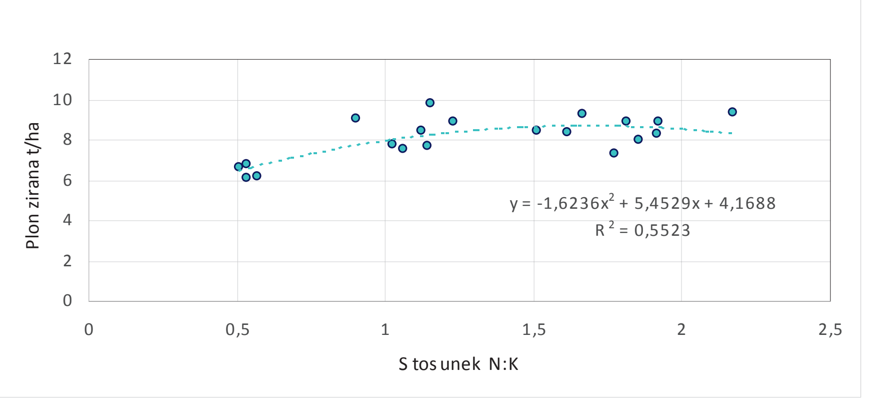
Tabela 2. Równania regresji wyrażające zależność plonu ziarna kukurydzy od stanu odżywienia kukurydzy w fazie kwitnienia

Warianty nawożenia	Równania regresji	R^2
Control	y=0,66248N + 1,68758Ca - 0,04846Zn + 0,21218Cu+3,30472 (*) (*) (*) (0,1) (*)	0,7725
WPN	y= 1,5054N + 8,6038P + 7,8139Mg - 0,3828 Cu+2,1419 (*) (*) (0,08) (*) (*)	0,890
WKN	y=-11,07159P -1,82593Ca + 7,49808Mg + 0,29821Zn -0,43821Cu-0,02338Fe+7,23142 (*) (0,08) (0,15) (*) (*) (0,1) (0,3)	0,7775
W25	y=2,91463N + 7,01066P - 3,39092Ca + 5,72388Mg - 0,06870 Zn - 0,08168Fe+5,42825 (*) (*) (*) (*) (*) (0,1) (*)	0,9367
WP50	y= 2,84562N + 1,29247K - 2,68725Ca + 11,31489Mg +0,28171Cu- 0,02820Mn – (0,7) (*) (*) (*) (*) (*) 0,04988Fe + 0,48438 (0,1) (*)	0,9467
WK50	y= 1,20371N + 11,57530P + 2,47886Ca -0,08248Zn -0,17443 Cu+2,9623 (*) (*) (*) (*) (0,2) (0,3)	0,7464
W100	y= 1,17919N + 3,67003P + 1,03716Ca + 4,61511Mg -0,02603Fe+4,3383 (*) (*) (0,08) (*) (*) (0,1)	0,8919
W100 (.P jako – PAPR.	Y= -1,74750K + 3,74243Ca-4,4643Mg + 0,10150Mn-0,03278Fe+8,43357 (*) (*) (*) (*) (*) (*)	0,877

p-poziom istotności

W większości analizowanych wariantów (z wyjątkiem 2 obiektów) stwierdzono, że składnikami warunkującym plon były: azot, fosfor, wapń i magnez oraz pojedynczo w z zależności od obiektu ujawniały się mikroskładniki (tabela 2).

Ważnym czynnikiem decydującym o zawartości danego składnika w roślinie jest koncentracja innych pierwiastków. Niezależnie od obiektu rośliny były niedożywione azotem w obydwu analizowanych terminach. Niedobór azotu w fazie kwitnienia został również w pełni potwierdzony poprzez analizę zależności plonu od stosunku N:K. Zależność plonu ziarna od relacji N:K wyrażona za pomocą równania regresji 2°, pozwoliła na wyznaczenie wartości optymalnej N:K = 1,67, która gwarantowała uzyskanie maksymalnego plonu ziarna na poziomie 9 $t \cdot ha^{-1}$. Taka relacja obu pierwiastków wskazuje na jednoczesną konieczność optymalizacji odżywienia kukurydzy zarówno azotem jak i potasem (ryc. 1).



Ryc. 1. Zależność plonu ziarna od stosunku zawartości N:K w liściach kukurydzy w fazie kwitnienia

5.3. Wpływ zróżnicowanego nawożenia mineralnego PK na akumulacja składników

Problematykę akumulacji makro i mikroskładników w fazie dojrzałości fizjologicznej przedstawiono w pracach A-2, A-3 i A-4. W celu wyjaśnienia wpływu badanego czynnika doświadczalnego na zawartość i akumulację składników przeprowadzono dwuczynnikową analizę wariancji w oparciu o model mieszany (ANOVA). W pierwszej części prac przeanalizowano zawartość składników w organach wegetatywnych i generatywnych kukurydzy, a w następnym etapie określono wartości akumulacji ocenianych pierwiastków w danym organie, całkowite pobranie oraz indeksy akumulacji ocenianych pierwiastków. W odniesieniu do zawartości fosforu i potasu (praca A-2) stwierdzono istotny wpływ czynnika doświadczalnego na kształtowanie różnic pomiędzy obiektami, ale nie w każdym przypadku zanotowano wzrost zawartości składników (P, K) w analizowanych organach w porównaniu do obiektu kontrolnego. Zawartość fosforu w analizowanych organach kukurydzy zmniejszała się w kierunku: ziarno> łodygi > liście > koszulki > rdzenie. Istotne różnice w zawartości tego składnika pod wpływem działania czynnika doświadczalnego stwierdzono w odniesieniu do ziarna i łodyg. *Niezależnie od analizowanego organu nie zanotowano natomiast istotnych różnic w zawartości fosforu w zależności od zastosowanej formy składnika w nawozie.* Zróżnicowane dawki fosforu w sposób niejednoznaczny wpływały na kształtowanie różnic zawartości tego pierwiastka w analizowanych organach pomiędzy obiektami.

Zawartość potasu w kukurydzy była zróżnicowana w zależności od organu i zmniejszała się w kierunku: pędy> rdzenie> koszuli > liście > ziarno. W każdym przypadku stwierdzono istotne zróżnicowanie zawartości K pod wpływem czynnika doświadczalnego. Szczególnie silna reakcja kukurydzy na brak nawożenia potasem oraz zmienne dawki tego składnika w nawozie uwidoczniła się w łodygach, a także w liściach i koszulkach *Forma fosforu aplikowanego w nawozie nie miała istotnego wpływu na zawartość P w analizowanych organach kukurydzy, a także całkowitą akumulację pierwiastka w roślinie*.

Całkowite pobranie azotu, fosforu i potasu przez kukurydzę było istotnie zróżnicowane przez działanie czynnika doświadczalnego (praca A-2). Najmniejsze wartości pobrania analizowanych składników odnotowano w wariancie kontrolnym. Niezależnie od poziomu nawożenia mineralnego stwierdzono istotny wzrost akumulacji makroskładników pod wpływem nawożenia mineralnego. Akumulacja fosforu w ziarnie zwiększała się wraz ze zmniejszaniem się dawki składnika w nawozie. Pominięcie w nawożeniu P lub K skutkowało znacznie mniejszą redukcją akumulacji azotu i fosforu niż potasu. Znaczący spadek pobrania potasu (26%) w porównaniu do wariantu optymalnie nawożonego azotem odnotowano w stanowisku bez potasu.

Czynnik doświadczalny w większym stopniu różnicował całkowite pobranie magnezu niż wapnia. Spośród badanych organów kukurydzy najwięcej magnezu akumulowało ziarno (56%), najmniej rdzenie (2%). Odmiennie kształtowała się struktura akumulacji wapnia w analizowanych organach, która zmniejszała się w kierunku: łodygi >liście>ziarno>rdzenie> koszulki.. W ziarnie zakumulowane było od 5,8% do 11% całkowitego pobrania wapnia.

Całkowite pobranie zarówno miedzi i manganu było również istotnie zróżnicowane przez działanie czynnika doświadczalnego (praca A-3). Nawożenie mineralne istotnie zwiększyło akumulację obydwu mikroskładników w porównaniu do obiektu kontrolnego. Nawożenie mineralne P i K w sposób niejednoznaczny różnicowało całkowitą akumulację miedzi i manganu. Dziesięcioletni brak nawożenia potasem w znacznie większym stopniu redukował całkowite pobranie zarówno Cu jak i Mn niż brak nawożenia fosforem. Różnica pomiędzy analizowanymi obiektami dla Cu była istotna statystycznie i wynosiła 15%. W przypadku manganu natomiast obiekty, na których pominięto nawożenie fosforem lub potasem nie różniły się istotnie.

Ważnym elementem oceny akumulacji składników w plonie końcowym kukurydzy jest rozdział pomiędzy organy ze szczególnym uwzględnieniem akumulacji składnika w ziarnie, czyli indeksu żniwnego akumulacji. Procentowy udział składników zgromadzonych w ziarnie względem całkowitej akumulacji pierwiastków w biomasie nadziemnej wykazał istotne zróżnicowanie pod wpływem nawożenia P i K. Azot i fosfor zakumulowane były w większości w ziarnie kukurydzy (60-70%), natomiast potas w łodygach (50-61%).

Nagromadzenie manganu w ziarnie wyrażone za pomocą indeksu MnIH kształtowało się w zakresie od 13,7 do 20,9% Znaczna część manganu (50-64% całkowitego pobrania) zgromadzona była w liściach kukurydzy, co wskazuje na słabą mobilność tego pierwiastka w roślinie. W przypadku cynku akumulacja składnika w ziarnie oscylowała w zakresie od 52,9% do 57,3%.

Niezależnie od analizowanego wariantu doświadczalnego analiza regresji wykazała, że plon ziarna kukurydzy w największym stopniu determinowany był przez całkowitą akumulację azotu.

Wykazano również wysoce istotną zależność plonu ziarna kukurydzy od całkowitej akumulacji magnezu w ziarnie, co wskazuje iż plonotwórcze działanie magnezu szczególnie wyraźnie zaznacza się w warunkach umiarkowanego zaopatrzenia roślin w azot.

Analiza korelacji uwzględniająca zależność pomiędzy plonem ziarna kukurydzy a akumulacją cynku w fazie dojrzałości pełnej, niezależnie od działania czynnika doświadczalnego wykazała, że wielkość plonu ziarna kukurydzy w największym stopniu determinowana była przez akumulację cynku w organach wegetatywnych (szczególnie koszulki).

5.4. Reakcja plonotwórcza kukurydzy

Reakcję plonotwórczą kukurydzy testowano w pięciu kolejnych sezonach wegetacyjnych (lata, 2007-2011). Wyniki otrzymane w przeprowadzonym eksperymencie przedstawiono w pracy A-1. Kukurydza w każdym roku badań uprawiana była na glebie charakteryzującej się średnią zasobnością w przyswajalny fosfor i potas. Niezależnie od roku badań w porównaniu do wariantu kontrolnego odnotowano istotny wzrost plonów ziarna na wszystkich obiektach nawożonych. Istotne różnice w plonach stwierdzono także między obiektami nawożonymi, co oznacza, że poziom nawożenia fosforem i potasem w warunkach prowadzonego doświadczenia miał istotny wpływ na wielkość plonu ziarna kukurydzy. Brak nawożenia tymi składnikami spowodował spadek plonów w porównaniu do wariantu optymalnie zbilansowanego względem dawki azotu. Wyjątek stanowił jedynie rok 2007, w którym brak nawożenia P nie skutkował redukcją plonu ziarna kukurydzy. Największy spadek plonów zanotowano w 2011 roku, czyli po dziesięciu latach braku nawożenia P i K. W porównaniu do obiektu optymalnie nawożonego redukcja plonu ziarna dla wariantów bez nawożenia fosforem lub potasem wynosiła odpowiednio 21,5% i 9,0%. Powyższa zależność potwierdza, ogólny pogląd, iż kukurydza jest gatunkiem o specyficznych wymaganiach względem fosforu.

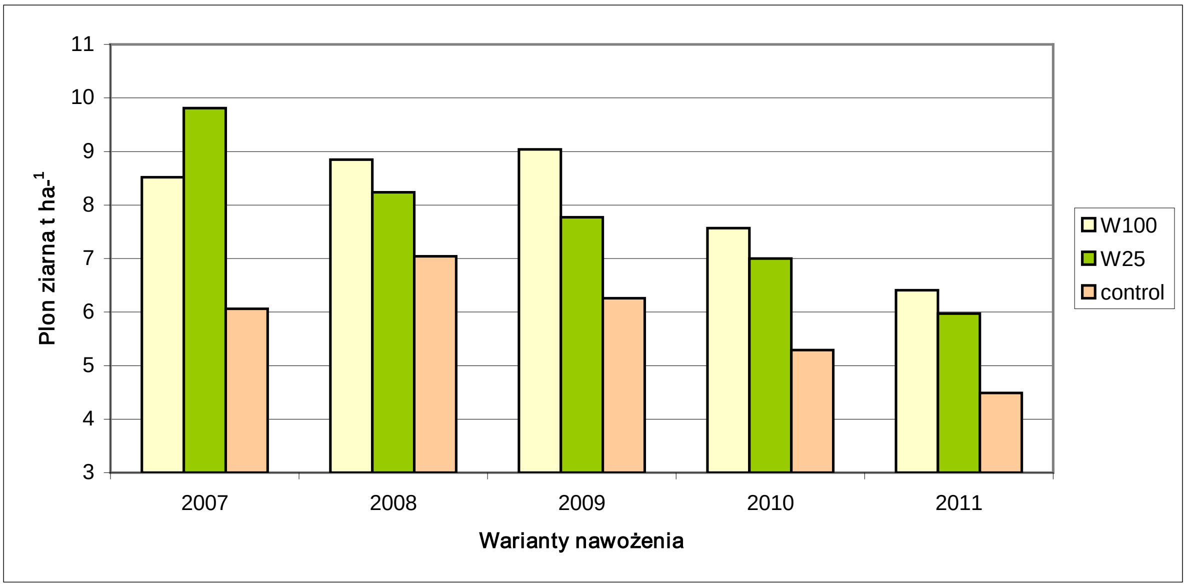
Analiza plonów ziarna kukurydzy w latach badań wskazuje, że wpływ czynnika nawożenia wzrastał w miarę trwania eksperymentu. Dodatkowo redukcja plonów zwiększyła się w połączeniu z niekorzystnym przebiegiem warunków pogodowych w 2011 roku, który kończył podjęte badania eksperymentalne. Znaczący deficyt wody w połączeniu z wysokimi temperaturami w kwietniu, maju i w czerwcu spowodował niezależnie od obiektu redukcję plonów, która w przypadku obiektu optymalnie nawożonego względem azotu (W100) w porównaniu do lat poprzednich średnio wynosiła 24%, natomiast w wariancie ze zredukowaną dawką P i K do 25% (W25) przedstawiała się na poziomie 27% (ryc.2). W stanowisku kontrolnym redukcja plonów ziarna uwzględniająca powyższe kryterium ograniczające plon wynosiła 30%.

Nie stwierdzono wpływu czynnika doświadczalnego na podstawowy element struktury plonu tj. masę tysiąca ziaren. W porównaniu do obiektu optymalnie nawożonego względem azotu zanotowano jedynie tendencję do spadku wartości tego parametru na wszystkich analizowanych obiektach (ryc. 3). Niezależnie od analizowanego wariantu wykazano istotną zależność pomiędzy plonem ziarna kukurydzy a MTZ, wyjątek stanowił jedynie obiekt, na którym dawkę P i K zredukowano do 25% względem wariantu optymalnie zbilansowanego względem azotu.

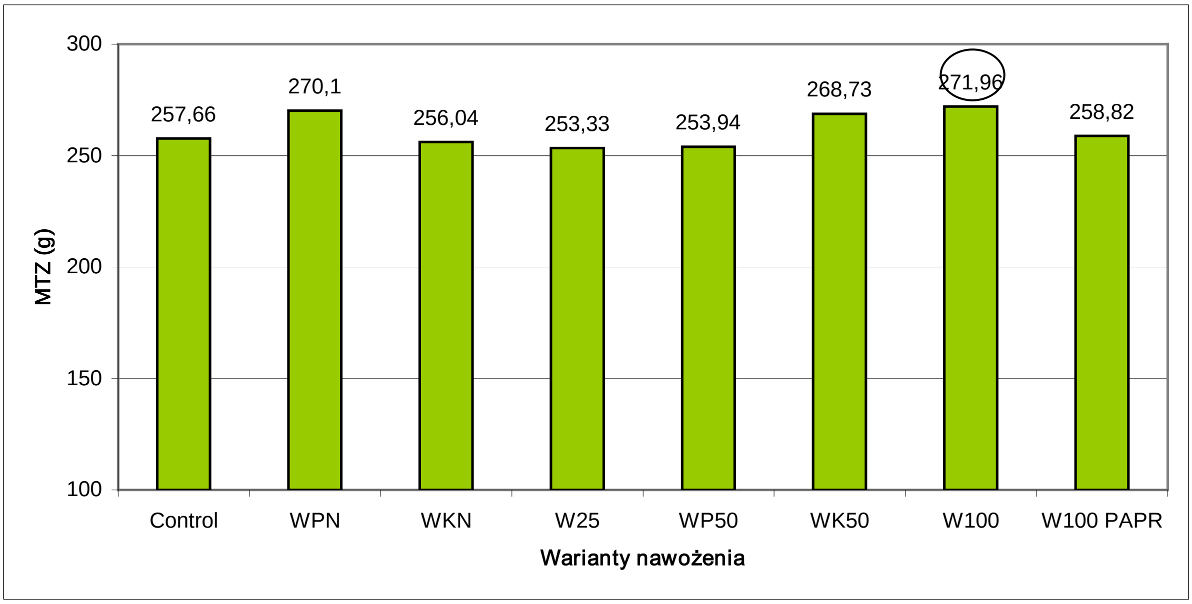
Tabela 3. Współczynniki korelacji pomiędzy plonem ziarna kukurydzy a masą tysiąca ziaren w zależności od poziomu nawożenia mineralnego P i K

Warianty nawożenia/Treatments							
Control	WPN	WKN	W25	WP50	WK50	W100	W100 P as PAPR
0,830*	-0,002	0,78*	0,81*	0,73*	0,72*	0,89*	0,57*

*p<0.05



Ryc. 2 Wpływ redukcji dawek fosforu i potasu na plonowanie kukurydzy w latach badań (2007-2011)



Ryc. 3. Wpływ zróżnicowanego nawożenia mineralnego P i K na wielkość masy tysiąca ziaren (MTZ)

6. WNIOSKI

Ocena stanu odżywienia kukurydzy w fazie 7-8 liści (BBCH17) wykazała stan niedożywienia roślin wszystkim analizowanymi składnikami mineralnymi, z wyjątkiem żelaza, którego zawartość kształtowała się powyżej dolnej wartości normatywnej. Zróżnicowane dawki fosforu i potasu istotnie różnicowały w początkowym stadium rozwoju kukurydzy jedynie koncentrację miedzi i manganu w liściach.

Odnotowano istotną zależność pomiędzy stanem odżywienia kukurydzy w fazie 7 w pełni rozwiniętych liści właściwych a plonem ziarna. Analiza regresji wykazała, że plon ziarna niezależnie od obiektu determinowany był przez zawartość składników w liściach kukurydzy w zakresie od 59% do 94%.

W drugiej ocenianej fazie krytycznej przydającej na stadium kwitnienia roślin stwierdzono, że rośliny wykazały stan niedożywienia azotem, fosforem, magnezem, cynkiem i miedzią. Czynnik doświadczalny istotnie różnicował zawartość wapnia, magnezu, cynku i miedzi w liściu podflagowym. Pod wpływem nawożenia mineralnego stwierdzono wzrost zawartości N, P, K i Mn w liściach kukurydzy na wszystkich analizowanych obiektach, natomiast nie zanotowano istotnych różnic pomiędzy badanymi wariantami, na których zastosowano nawożenie mineralne.

Wykazano również silną istotną zależność plonu od zawartość składników w liściach w fazie kwitnienia kukurydzy, którą potwierdzają wysokie wartości współczynników determinacji kształtujące się w przedziale od 74 do 95%.

Zróżnicowane dawki fosforu i potasu w warunkach prowadzonego doświadczenia istotnie kształtowały wielkość plonu ziarna kukurydzy. Działanie czynnika doświadczanego nie było jednoznaczne i wykazało dużą zmienność w latach badań. Kukurydza reagowała większą redukcją plonu ziarna na brak nawożenia fosforem niż potasem.

Ocena zależności plonu ziarna kukurydzy od stosunku N:K w fazach krytycznych wykazała wyższą wartość prognostyczną niż zależność plonu od pojedynczych zawartości analizowanych składników. Optymalny stosunek N:K niezależnie od badanego obiektu kształtował się w zakresie 1,65 - 2 i gwarantował uzyskanie plonu ziarna na poziomie 8-9 t $\cdot ha^{-1}$.

Brak reakcji plonotwórczej i żywieniowej kukurydzy na formę nawozu fosforowego jednoznacznie wskazuje na zbliżone działanie plonotwórcze superfosfatu i częściowo zakwaszonego fosforytu jako nośników fosforu dla kukurydzy.

System gospodarowania fosforem i potasem w uprawie kukurydzy na glebie o średniej zasobności, polegający na dostarczeniu składników w ilości równej wyniesieniu ich z plonem ziarna w dłuższym przedziale czasu prowadzi do: (1) nadmiernego zubożenia gleby w przyswajalne formy składników, (2) niedożywienia roślin w trakcie wegetacji; (3) zakłócenia homeostazy żywieniowej, a w konsekwencji jest przyczyną redukcji plonu i spadku produktywności stanowiska.

Analizy chemiczne gleb po zakończeniu badań (2011r.) wskazują, że w wariantach nawożonych fosforem i potasem w porównaniu do roku 2007 stwierdzono spadek zawartości P i K przyswajalnego w glebie, który w porównaniu do roku 2007 wynosił odpowiednio 15,6% (43,2 mg P kg^{-1}) i 13,8% (97,4 mg K kg^{-1}).

7. Załączniki:

Załącznik 1. Prace stanowiące rozprawę doktorską

Załącznik 2. Oświadczenia współautorów prac określające indywidualny udział autora w każdej publikacji

Załącznik 1

A1

Journal of Elementology ISSN 1644-2296

Bąk K. Gaj R. 2016. *Effect of differentiated phosphorus and potassium fertilization on maize grain yield and plant nutritional status at a critical growth stage.* J. Elem., 21(2): 337-348. DOI: 10.5601/jelem.2015.20.3.996

EFFECT OF DIFFERENTIATED PHOSPHORUS AND POTASSIUM FERTILIZATION ON MAIZE GRAIN YIELD AND PLANT NUTRITIONAL STATUS AT A CRITICAL GROWTH STAGE

Krzysztof Bąk[1], Renata Gaj[2]

[1]Rychnowy, Akacjowa 10, 77-300 Człuchów, bakkrzysztof@wp.pl
[2]Chair of Agricultural Chemistry and Environmental Biogeochemistry
Poznań University of Life Sciences

Abstract

Optimal nutrition of cultivated plants at critical growth stages is of great importance for the achievement of full crop yield potential. The aim of this study was to assess the maize yield response and plant nutritional status at a critical stage of growth (BBCH 17) under the most favourable and reduced fertilization with phosphorus and potassium. It was assumed that the nutritional status of maize at BBCH 17 stage significantly influenced the plant growth and yielding. The hypothesis was tested in a one-factorial trial, carried out on the maize variety Veritis in 2007-2011, which was a part of a long-term study started in 2000 according to a randomized complete block design. The factor tested comprised different phosphorus and potassium doses applied at constant levels of nitrogen and magnesium fertilization. The yields of maize significantly differed between the treatments and in relation to the control. In each year, maize responded with a lower yield to the no-phosphorus treatment when compared to the no-potassium treatment. Irrespective of the fertilization variants, the content of the nutrients tested (except iron) was below the standard value. A significant relationship was shown between the nutritional status of maize at the stage of 7 leaves unfolded (BBCH 17) and grain yield. The coefficients of determination ranging from 59% to 94% showed that, irrespective of which treatment was applied, the mineral nutrient content in maize leaves at BBCH 17 stage had the strongest influence on the maize yield.

Keywords: maize, phosphorus and potassium rates, nutritional status.

dr hab. Renata Gaj, Chair of Agricultural Chemistry and Environmental Biogeochemistry, Poznań University of Life Sciences, Wojska Polskiego str. 71F, 60-625 Poznań, Poland, email: grenata@up.poznan.pl

INTRODUCTION

Many producers believe that maize is a crop with low nutritional requirements, as a result of which the yields harvested are often much lower than could be expected on fertile sites. A satisfying economic result can be achieved only when maize cultivation relies on adequate agricultural techniques that include plant nutrition management as well as the recognition of a factor or a group of factors responsible for maize yielding. The right fertilization practice plays a key role in enhancing yields of cultivated plants and achieving a sustainable crop production increase (Huang et. al. 2010).

Knowledge of the actual availability of nutrients in soil and their specific uptake is crucial for preparing an adequate maize fertilization plan. The specific nutrient uptake index reflects the amount of grain yield in relation to a given nutrient accumulated in the aerial biomass at the stage of crop maturity (harvest) (Grzebisz, Gaj 2007). Literature has thus far provided scarce information on the content of soil nutrients that would allow one to determine fertilization doses of phosphorus (P) and potassium (K) that ensure the maximum maize yield. The currently available research results indicate that 50% - 80% of P applied as fertilizer is absorbed by soil, and no information is available regarding a P fertilizer dose which could ensure a sufficient supply of available form of this nutrient without causing adverse effects on yields (Shenoy and Kalagudi 2005, Vogeler et al. 2009). Another critical element in maize cultivation is potassium, whose soil deficiency has become a global problem (Dobermann et al. 1998, Hedlund et al. 2003, Malo et al. 2005, Tan et al. 2012). In Europe, more than 25% of soils are low in available K (Rőmheld, Kirkby 2010). Smil (1999) reported that potassium fertilizers, in contrast to phosphorus, are applied at much lower doses, and less than 50% of the K removed by crops is replenished. In Poland, it is alarming that the consumption of potassium fertilizers has been dramatically declining, which in the near future can become a significant limiting factor for the stability of yields of maize and other agricultural plants. It is therefore urgent to monitor the soil K reserves in order to make precise fertilizer recommendations (Zorb et al. 2014). The risk of yield reduction can be minimized by a balanced mineral fertilization plan, including all nutrients (Öborn et al. 2005). The effects of phosphorus and potassium on agricultural yields arise mainly from the role these nutrients play in counteracting the impact of biotic and abiotic stresses. Plants fully supplied with P and K are considerably less vulnerable to water stress, low temperatures and pathogenic agents (Ma et al. 2006). Yield-forming actions of phosphorus and potassium are dissimilar as these nutrients produce different effects on plant growth during the plant growing season. However, both nutrients affect the nitrogen management in high-yield agricultural crops (Marschner 1996).

The aim of the present study was to assess the yield response of maize and its nutritional status at a critical growth stage (BBCH 17) under the conditions of lower than optimal phosphorus and potassium fertilization.

MATERIAL AND METHODS

In 2007-2011, a single factor experiment was conducted on the maize variety Veritis (FAO: 230-240) on a field lying in a village called Wieszczyczyna, near Śrem (52°02′ N 17°05′E). The trial belonged to a long-term study carried out since 2000 and established in a randomized complete block design with four replications. The experimental factor comprised differentiated mineral fertilization doses of phosphorus and potassium (Table 1). The experiment was set up on lessive soil (soil quality class IIIb in the Polish soil classification system) developed from shallow light clayey sands on glacial tills. The soil properties are summarized in Table 2. Winter wheat was grown as a preceding crop before maize during the experiment. Wheat straw

Table 1

Design of field experiment

Treatment	Description
Control (KA)	no fertilizer application in 2007-2011
WPN	no phosphorus fertilization; optimal fertilization with other nutrients (nitrogen, potassium, magnesium)
WKN	no potassium fertilization; optimal fertilization with other nutrients (nitrogen, potassium, magnesium)
W25	25% of PK recommended dose as compared to optimally fertilized treatment; optimal fertilization with N and Mg
WP50	50% of P recommended dose as compared to optimally fertilized treatment; the rest of nutrients were applied at optimal doses
WK50	50% of K recommended dose as compared to optimally fertilized treatment; the rest of nutrients applied at optimal dose
W100	100% of P and K recommended dose; treatment optimally balanced with regard to nitrogen
W100 P as PAPR)	100% of P and K recommended dose; phosphorus applied as partially acidulated phosphate rock (PAPR)

Table 2

Soil physical and chemical properties

Year	P available (mg P kg^{-1})	K available (mg K kg^{-1})	Sand (%)	Silt (%)	Clay (%)	pH 1M KCl
2000 (establishment of the long-term experiment)	85.0	145.0	84	10	6	6.55
2007	51.2	113.1	84	10	6	4.90
2011 (after harvest)	43.2	97.4	84	10	6	4.60

was removed from the field after harvest each year. Maize was seeded with a seeding machine coupled with a seed drill (rows spaced at 0.75 m). All cultivation and harvest practices were carried out in accordance with the agricultural requirements for maize. An optimal fertilization dose (W100) was determined by taking into account the soil nutrient availability, specific uptake and expected yield in each year. Mineral fertilization doses applied in the study are presented in Table 3. The phosphorus dose for the W100 treatment (optimally balanced with reference to nitrogen) was 26 kg P ha^{-1} $year^{-1}$ (except for 2007: 35 kg P ha^{-1}), and potassium doses ranged from 100 kg K ha^{-1} to 133 kg K ha^{-1}. P and K doses applied in the subsequent treatments were reduced to 50% (W50) and 25% (W25) of treatment W100. Additionally, there were control treatments: WKN and WPN, with constant doses of nitrogen and magnesium and no potassium or phosphorus added, respectively. P, K and Mg fertilization was performed in line with the experimental design after the harvest of the preceding crop plants. Potassium was applied as potassium chloride (60% K_2O), phosphorus (P_2O_5) – as single superphosphate, and magnesium – as kieserite (27% MgO). The W100 variant included an additional treatment with partially acidulated phosphate rock (W100-PAPR), applied as an alternate source of phosphorus for single superphosphate. Phosphate rock used in the study contained 10.2% of P and its acidification was 50% (i.e. the amount of sulphuric acid used up during the technological process run to obtain the product was 50% of the amount necessary for the production of single superphosphate). Fertilization with nitrogen was carried out twice (70% before maize seeding and 30% at the stage of 4 leaves unfolded). In all the treatments analyzed, the plants for chemical analyses were randomly collected (10 plants/treatment) at the stage of 7 leaves unfolded (BBCH-17) and at the stage of technological maturity (BBCH 89). The yield of maize grain (app. 70% dry weight) was determined at BBCH 89 stage over an area of 24 m^2 (two 16-meter-long central rows). The total grain yield value was adjusted to the 14% moisture content. The analysis of the content of nutrients was carried out using the standard methods (N – Kjeldahl's method, P – calorimetrically, K and Ca – flame photometry, Mg, Zn, Cu, Mn, Fe – atomic absorption spectroscopy AAS).

Table 3

Mineral fertilization dose during the study, in 2007-2011 (kg ha^{-1})

Years	Nutrients (kg ha^{-1})			
	N	P	K	Mg
2007	120	35	100	16
2008	120	26	125	16
2009	150	26	133	16
2010	150	26	125	16
2011	150	26	125	16

Statistical tests

The results of the maize grain yield and plant nutrient content were tested with two-way Anova. The factors analyzed were: the study year and the dose of mineral fertilization with phosphorus and potassium. Multiple regression analysis was applied for an evaluation of the cause and effect relationships between the parameters. The regression model was built based on an algorithm used in backward stepwise regression with the bidirectional elimination testing at each step for variables to be included or excluded. The final model determined the variables with decisive effects on the maize nutrient content and grain yield.

RESULTS AND DISCUSSION

Yield response

The analysis of variance of the maize grain yield achieved during the experiment showed highly significant differences between the treatments with phosphorus and potassium mineral fertilization (Figure 1). In each year, a significant increase of yield was observed in all the treatments when compared to the control. Significant differences were also observed between the treatments tested, which means that the phosphorus and potassium doses applied had significant effects on the maize yield quantity. The largest yields (7.5-9.8 t ha^{-1}) were harvested in 2007 and 2008. In general, the effect of mineral fertilization was indistinct and differed in the study years. The treatments with no phosphorus (WPN) and potassium (WKN) deserve special attention. The lack of fertilization with these nutrients resulted in a maize yield decrease when compared to the treatment optimally balanced with re-

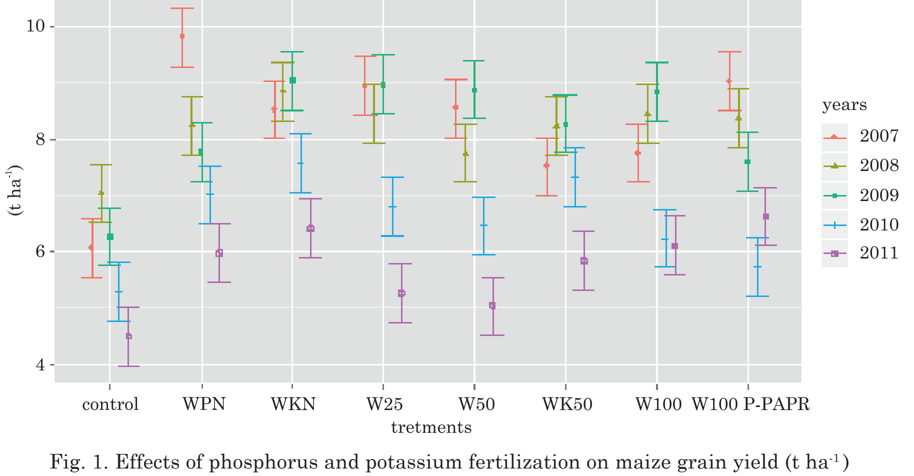


Fig. 1. Effects of phosphorus and potassium fertilization on maize grain yield (t ha^{-1})

gard to nitrogen (W100). The lack of P fertilization caused a decrease of maize yield in all the years except in 2007. The highest yield decrease was observed in 2011, i.e. 10 years of P and K fertilization absence. Yield reduction in WPN and WKN treatments was 21.5% and 9.0%, respectively, when compared to W100 treatment. The relationship observed confirms the common view that maize has specific requirements with regard to phosphorus. Shenoy and Kalagudi (2005) believe that an insufficient amount of available P can be responsible for a 10% -15% yield reduction compared to the maximum yield. Data reported in literature on phosphorus fertilization of various agricultural plants tested in long-term studies indicate that yield reduction due to the lack of P fertilization appears after a considerably long time interval (Jouany et al. 1996, Stępień, Mercik 1999, Kunzova, Hejcman 2010). Shen et al. (2004) observed yield response in plants cultivated without P fertilization after 11 years. Studies conducted by Gaj (2012) on winter triticale showed yield reduction after 10 years of P and K fertilization absence (5% and 13%, respectively). P deficiency is a crucial factor in tropical regions and in calcareous soils (Hinsinger 2001). Huang et al. (2010) showed that unbalanced mineral fertilization increased maize yield in a short-term time interval, although it affected negatively soil nutrient availability in a long-term perspective. This regularity was confirmed in the present study when the following consequences were observed after 10 years of soil cropping: a decrease of soil available nutrient contents (lower soil valuation class) as well as a change of soil reaction from slightly acidic to acidic. As a general rule, a decrease of soil pH value results in an increase of the exchangeable aluminum content in soil. It all negatively affects agricultural plants by inhibiting the root system growth and decreasing the plant's capability to uptake water and mineral nutrients. On the whole, the value of soil reaction dropping below the optimal value for a given nutrient has a negative effect on the crop yield response. Meanwhile, intensive processes occur in soil that are associated with regression of available forms of phosphorus, and the content of base cations decreases. Economic effects of redundant soil acidification are reflected in yield loss quantity, which is a product of many, often mutually dependent processes (Van Breemen et al. 1983, Marschner 1991, Kidd, Proctor, 2001, Grzebisz et al. 2006). Under the conditions of the present study, the unbalanced mineral fertilization associated with acidic soil reaction and the removal of preceding crop straw from the field resulted in a decreasing trend for maize yield quantity, observed most distinctly in the last year. Similar maize response to analogous factors was reported by other authors (Xu at al. 2003, Zhang, Xu 2005). The results of this study indicated that maize showed differentiated response depending on the chemistry of the phosphorus fertilizer applied (Figure 1). In 2009 and 2010, considerable yield losses were observed (16% and 30%, respectively) in the treatment with partially acidulated phosphate rock when compared to the single superphosphate treatment. The response to a fertilizer's chemical structure indicates that yield forming actions of the above fertilizers as P providers for maize cannot be viewed as identical. Studies by Kanabo, Gilkes (1988) proved that no significant yield response to phosphate rock (phosphorite) application should be expected under the conditions of soils with high P sorption capacity coinciding with low cation-exchange capacity (CEC), precipitation, organic matter content and microbial activity. According to literature (Vanlauwe et al. 2000, Li et al. 2001, Pypers et al. 2007), positive effects of rock phosphate on maize cultivation rely upon legume plants used in crop rotation, which act as acidifiers of the rhizosphere.

Maize demonstrates a strong demand for potassium, necessitated by this plant's production of abundant biomass. Under the conditions of the present study, maize yield response to differentiated K rates varied in the years. In comparison with the treatment optimally balanced with regard to nitrogen, yield increasing trend as a result of a K dose applied was observed only in 2007 (Figure 1). In the other years, and especially in 2011, opposite relationships were found, irrespective of the amount of K applied. Maize yield response to potassium fertilization was a result of maize cultivation in the soil with low contents of available potassium. According to Szczepaniak (2004), positive yield response of an agricultural plant to K fertilization can be expected under the conditions of low availability of soil potassium and water stress during the plant growing season. Merbach et al. (1999) showed that at medium potassium availability in the soil, reduced K fertilization doses resulted in a decrease of agricultural plants' yields. A decreasing trend was the strongest in root crops and the weakest – in cereals. On the other hand, studies carried out by Gaj (2010*a*,*b*) in soils with medium K availability showed no significant direct effects of differentiated K doses or long-term absence of K fertilization on yields of wheat and winter rape.

The group of maize yield limiting factors also included mechanisms other than P and K actions. First of all, water and temperature conditions during the vegetation season should be implicated. Maize needs large quantities of water, since it promptly produces much vegetative biomass, which results in an almost twice as much yield as in other cereals. During the season, maize water requirements change (first critical phase occurs at the stage of 7 leaves unfolded). Regarding the weather as a factor, the least favourable conditions for maize yielding during the present study were observed in 2011. Considerable water deficiency associated with high temperatures in April, May and June caused yield reduction (on average by 27%, irrespective of the treatment applied) when compared to the other years. Rainfall measured in April, May and June 2011 (data obtained from the Institute of Meteorology and Water Management, Poznań) was only 19%, 29% and 75%, respectively, of the long-term precipitation averages. One of the main tasks of a farmer is to make the most of soil water (preventing surface runoff through securing good water infiltration down to the soil profile) as well as to enable cultivated plants to effectively manage water throughout their growth. The latter relies upon proper plant nutrition with potassium.

Nutrient content at the critical growth stage

The assessment of the maize nutritional status was carried out at the stage of 7 leaves unfolded – BBCH 17 (Table 4), based on the limit values

Table 4

Effects of different phosphorus and potassium fertilization doses on nutrient content in maize leaves (means of data from 2007-2011)

Treatments	(g kg^{-1} DM)					(mg kg^{-1} DM)			
	N	P	K	Ca	Mg	Zn	Cu	Mn	Fe
Control	31.00^{b*}	2.026^{c}	27.00^{b}	2.923^{a}	1.880^{b}	18.98^{b}	4.733^{abc}	17.00^{c}	147.3^{a}
WPN	36.76^{a}	2.111^{bc}	28.22^{ab}	2.919^{a}	1.785^{b}	22.90^{ab}	4.797^{abc}	30.26^{ab}	138.9^{a}
WKN	37.59^{a}	2.454^{a}	31.08^{a}	2.775^{a}	1.655^{b}	25.89^{a}	5.192^{ab}	31.58^{a}	139.2^{a}
W25	37.21^{a}	2.327^{ab}	28.48^{ab}	2.621^{a}	1.620^{b}	23.49^{a}	4.456^{c}	25.05^{b}	144.8^{a}
WP50	37.57^{a}	2.114^{bc}	28.65^{ab}	2.815^{a}	1.790^{b}	23.10^{ab}	5.231^{a}	30.20^{ab}	143.3^{a}
WK50	38.72^{a}	2.310^{ab}	26.90^{b}	2.862^{a}	2.435^{a}	24.00^{a}	4.356^{c}	28.43^{ab}	153.3^{a}
W100	38.00^{a}	2.083^{bc}	29.32^{ab}	2.829^{a}	1.630^{b}	22.97^{ab}	4.490^{bc}	27.25^{ab}	131.8^{a}
W100 P as PAPR	37.08^{a}	2.276^{abc}	29.41^{ab}	2.860^{a}	1.690^{b}	22.45^{ab}	4.406^{c}	29.52^{ab}	154.2^{a}

* means with the same letter are not significantly different

and with the use of mean values obtained in all the years, 2007-2011 (Schulte, Kelling 2000). The results showed that, notwithstanding the treatment applied, the plants were malnourished with both macro- and microelements. Iron was an exception because its content in maize plants was above the lower limit of the standard value. No significant differences were found in the phosphorus and potassium content in maize leaves between the treatments tested irrespective of the fertilization applied. Numerous literature data (Woodend, Glass 1993, Yang et al. 2004, Damon, Rengel 2007) indicate that genetic factors rather than a potassium dose applied as a fertilizer affect the K content of plants. The differences in adsorption of K among different plant species are attributed to variations in the root structure, such as root density, rooting depth and root hair length (Nieves-Cordones et al. 2014). Positive correlations between K uptake efficiency and root hair length in K-depleted soils have been reported for maize, and oilseed rape (Jungk 2001).

In the present study, the differentiated P and K rates applied had no significant effect on the content of nitrogen, calcium, magnesium and iron in plants and affected only the concentrations of copper and manganese. The content of calcium and magnesium in maize plants was particularly low. The reasons behind Ca and Mg deficiency are complex as this may result from both Ca and Mg shortage in soils as well as disturbed processes of nutrient uptake and transport within the plant during its growth. Calcium and manganese uptake is associated with the youngest root tissues, whose growth can be hindered by toxic aluminum in soil (White 2000). In the present study, the low content of Ca and Mg found in maize plants was due to the acidic soil reaction (pH from 4.7-5.12) observed since 2006 (after wheat harvest and the onset of a trial with maize cultivation) as well as the unfavourable weather conditions during the study.

Regression analysis concerning dependencies between maize grain yield and plant nutrient content at BBCH 17 stage observed in all the treatments showed significant relationships for the majority of the nutrients, and these were the most distinctly expressed for nitrogen, iron, zinc and manganese. The relationships for the treatments described by regression models are presented in Table 5. In all the treatments, the contribution of nutrients to

Table 5

Regression models of maize grain yield as the function of leaf nutrient content at BBCH 17 stage

Treatments	Regression models /(p^* – value)	R^2
Control	y = 0.757N + 3.367Ca – 0.111Zn + 0.003Fe + 2.273 (0.028) (0.175) (< 0.01) (0.073) (0.053)	0.7904
WPN	y = 0.546N – 29.529P + 0.578K – 11.084Mg + 0.042Mn + 0.006Fe + 10.240 (0.107) (< 0.01) (0.075) (0.061) (0.028) (< 0.01) (< 0.01)	0.9004
WKN	y = 0.810N – 5.013P + 0.0588Zn – 0.460Cu + 0.038Mn + 0.010Fe + 7.285 (< 0.01) (< 0.01) (< 0.01) (< 0.01) (0.043) (< 0.01) (< 0.01)	0.9375
W25	y = –1.660K – 2.995Ca + 0.583Zn + 0.193Mn + 0.005Fe + 4.881 (0.213) (< 0.01) (0.040) (0.107) (< 0.01) (0.126)	0.5922
WP50	y = 0.825N – 1.303K + 3.489Ca + 0.193Mn – 0.008Fe + 4.881 (0.213) (< 0.01) (0.040) (0.107) (< 0.01) (0.126)	0.8537
WK50	y = 1.018N + 6.810Mg + 0.065Zn + 0.578Cu – 0.088Mn – 0.008Fe + 6.448 (< 0.01) (0.064) (0.050) (0.061) (0.128) (< 0.01)	0.8346
W100	y = 1.503N – 11.192P – 5.404Ca + 10.110Mg + 0.037Zn + 3.120 (< 0.01) (0.065) (0.056) (0.061) (0.128) (< 0.01)	0.7815
W100 (P as PAPR)	y = 0.384N – 8.895P + 0.519K + 0.037Zn + 0.007Fe + 4.692 (0.103) (0.015) (0.045) (0.167) (< 0.01) (< 0.01)	0.8957

* p – empirical level of significance

shaping maize yield was substantial, which was confirmed by high values of the coefficients of determination ranging from 59% to 94%. The relationships observed suggested that the role of nutrients in yield formation gained importance in cases when the nutritional homeostasis was more severely impaired.

CONCLUSIONS

1. Under the conditions of the present study, differentiated rates of phosphorus and potassium fertilization significantly influenced the formation of maize grain yield. The action of the experimental factor was equivocal and showed high variability in the study years.

2. Maize responded with a higher yield reduction to the absence of phosphorus fertilization when compared to that of potassium.

3. The assessment of maize nutritional status at the stage of 5 - 7 leaves unfolded showed plant malnutrition with regard to all the mineral nutrients tested, except for iron, whose content was above the lower limit of the standard.

4. A significant relationship was found between the maize nutritional status at the stage of 5-7 leaves unfolded and grain yield. Regression analysis showed that, irrespective of the treatment applied, maize yield was determined in the range of from 59% to 94% by the nutrient content at 7 leaves unfolded.

ACKNOWLEDGEMENTS

We express our sincere thanks to dr Anna Budka for help in statistical calculations as well as her valuable suggestions and comments on the manuscript

REFERENCES

Damon P.M, Rengel Z. 2007. *Wheat genotypes differ in potassium efficiency under glasshouse and field conditions*. Aust. J. Res., 58: 816-825.

Dobermann A., Cassan K.G., Mamarii C.P., Sheehy J.E. 1998. *Management of phosphorus, potassium, and sulphur in intensive, irrigated lowland rice*. Field Crop Res., 56: 113-138.

Gaj R. 2010*a*. *Effect of different level of potassium fertilization on winter oilseed rape nutritional status at the initiation of the main stem growth and on the seed yield*. Oilseed Crops, 31: 111-121. (in Polish)

Gaj R. 2010*b*. *Influence of different potassium fertilization level on nutritional status of winter wheat and on yield during critical growth stage*. J. Elem., 15(2), 269-277.

Gaj R. 2012. *The effect of different phosphorus and potassium fertilization on plant nutrition in critical stage and yield of winter triticale*. J. Central Europ. Agric., 13(4): 704-716. DOI: 10.5513/JCEA01/13.4.1116

Grzebisz W., Diatta J.B., Szczepaniak W. 2006. *Productive and ecological backgrounds of arable soil liming*. Fertilizers Fertilization, 2: 69-85.

Grzebisz W., Gaj R. 2007. *Integrated production system of maize*. IOR-PIB, Poznań, 19-24. ISBN 978-83-89867-16-2. (in Polish)

Hedlund A., Witter E., An B.X. 2003. *Assessment of N, P, and K management by nutrient balances and flows on peri-urban smallholder farms in southern Vietnam*. Eur. J.Agron., 20: 71-87.

Hinsinger P. 2001. *Bio-availability of soil inorganic P in the rhizosphere as affected by root induced chemical changes: a review*. Plant Soil, 237: 173-195.

Huang S., Zhang W., Yu X., Huang Q. 2010. *Effects of long-term fertilization on corn productivity and its sustainability in an Ultisol of Southern China*. Agric. Ecosyst. Environ., 138: 44-50.

Jouany C., Colomb B., Bosc M. 1996. *Long-term effects of potassium fertilization on yield and fertility status of calcareous soils of south-west France*. Eur. J. Agron. 5: 287-294.

Jungk A. 2001. *Root hairs and the acquisition of plant nutrients from soil*. J. Plant Nutr. Soil Sci., 164: 121-129.

Kanabo I.A.K., Gilkes R.J. 1988. *The effect of the level of phosphate rock application on its dissolution in soil and on bicarbonate-soluble phosphorus*. Fert. Res., 16: 67-85.

Kidd P.S., Proctor J. 2001. *Why plants grow poorly on very acid soils: Are ecologists missing the obvious*? J. Exp. Bot., 52, 357: 791-799.

Kunzova E., Hejcman M. 2010. *Yield development of winter wheat over 50 years of nitrogen, phosphorus and potassium appliction on greyic Phaeozem in the Czech Republic*. Eur. J. Agron., 33:166-174.

Li L., Sun J., Zhang F., Li X., Yang S., Rengel Z. 2001. *Wheat/maize or wheat/soybean strip intercropping*. I. *Yield advantage and interspecific interactions on nutrients*. Field Crops Res., 71: 123-137.

Ma Q., Niknam S.R., Turner D.W., 2006. *Responses of osmotic adjustment and seed yield of Brassica napus and B. junacea to soil water deficit at different growth stages*. Aust. J. Agric. Res., 57: 221-226.

Malo D.D., Schumacher T.E., Dooliile J.J. 2005. *Long-term cultivation impacts on selected soil properties in the northern Great Plains*. Soil Till. Res., 81: 277-291.

Marschner H. 1991. *Mechanisms of adaptation of plants to acid soils*. Plant Soil, 134: 1-20.

Marschner H., Kirkby E., Cakmak J. 1996. *Effect of mineral nutritional status on shoot-root partitioning of photo assimilates and cycling of mineral nutrients*. J. Exp. Bot., 47: 1255-1263.

Merbach W., Schmidt L., Wittenmayer L. 1999. *Die Dauerdungungversuche in Halle (Saale*), B.G. Teubner, Stuttgart-Leipzing, 56-65.

Nieves-Corones M., Aleman F., Martinez V., Rubio F. 2014. *K^+ uptake in plant roots. The systems involved, their regulation and parallels in other organisms*. J. Plant Physiol., 171: 688-695.

Öborn I., Andrist-Rangel Y., Askekaard M., Grant C.A., Watson C.A., Edwards A.C. 2005. *Critical aspects of potassium management in agricultural systems*. Soil Use Manage., 21: 102-112.

Pypers P., Huybrighs M., Diels J., Abaidoo R., Smolders E., Merckx R. 2007. *Does the enhanced P acquisition by maize following legumes in a rotation result from improved soil P availabilty?* Soil Biol. Biochem., 39: 2555-2566.

Rőmheld V., Kirkby E.A. 2010. *Research on potassium in agriculture: needs and prospects*. Plant Soil., 335:155-180.

Schulte E., Kelling K. 2000. *Plant analysis: A diagnostic tool*. University of Wisconsin-Madison. www.ces.pardue.edu/extmedia/NCH/NCH-46.html

Shen J., Li R., Zhang F., Fan J., Tang C., Rengel Z. 2004. *Crop yields, soil fertility and phosphorus fractions in response to long-term fertilization under the rice monoculture system on a calcareous soil*. Field Crops Res., 86: 225-238.

Shenoy V.V., Kalagudi G.M. 2005. *Enhancing plant phosphorus use efficiency for suitable cropping*. Biotechnol. Adv., 23: 501-513.

Smil V. 1999. *Crop residues: Agriculture's largest harvest*. Bioscience, 49 :299-308.

Stępień W., Mercik S. 1999. *Changes in the phosphorus and potassium content in soil and crop yielding in a 30-year time period, on soil fertilized and not fertilized with these nutrients*. Zesz. Probl. Post. Nauk Rol., 467: 269-278. (in Polish)

SZCZEPANIAK W. 2004. *Plants' response to potassium fertilization*. J. Elem., 9(4): 57-66. (in Polish)

TAN D., JIN J., JIANG L., HUANG S., LIU Z. 2012. *Potassium assessment of grain production in North China*. Agric. Ecosyst. Environ., 148: 65-71.

VAN BREEMAN, N., NULDER J., DRISCOLL C. T. 1983. *Acidification and alkalinization of soils*. Plant Soil, 75: 383-308.

VANLAUWE B., DIELS J., GINGA N., CARSKY R.J., DECKERS J., MERCKY R. 2000. *Utilization of rock phosphate on a representative toposequence in the Northern Guinea savanna zone of Nigeria: Response by maize to previous herbaceous legume cropping and rock phosphate treatments*. Soil Biol. Biochem., 32: 2079-2090.

VOGELER I., ROGASIK J., FUNDER U., PANTEN K., SCHNUG E. 2009. *Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake*. Soil Till. Res., 103: 137-143.

WHITE P.J. 2000. *Calcium channels in higher plants*. Biochim. Biophys. Acta, 1465: 171-189.

WOODEND J.J., GLAS A.D.M., 1993. *Genotype-environment interaction and correlation between vegetative and grain production measures of potassium use-effciency in wheat (T. aestivum* L.*) grown under potassium stress*. Plant Soil, 151:39-44.

XU R., ZHAO A., LI Q., KONG X., JI Q. 2003. *Acidity regime of Red Soils in a subtropical region of southern China field conditions*. Geoderma, 115: 75-84.

YANG X.E., LIU J.X., WANG W.M., YE Z.Q., LUO A.C. 2004. *Potassium internal use efficiency relative to growth vigor, potassium distribution and carbohydrate allocation in rice genotypes*. J. Plant Nutr., 27:837-852.

ZHANG M.K., XU J.M . 2005. *Nestorian of surface soil fertility of an eroded red soil in southern China*. Soil Till. Res., 80: 13-21.

ZŐRB CH., SENBAYRAM M., PEITER E. 2014. *Potassium in agriculture – status and perspectives*. J. Plant Physiol., 171: 656-669.

A2

Fragm. Agron. 33(1) 2016, 7–19

ACCUMULATION OF NITROGEN, PHOSPHORUS AND POTASSIUM IN MATURE MAIZE UNDER VARIABLE RATES OF MINERAL FERTILIZATION

Krzysztof Bąk[1], Renata Gaj[2], Anna Budka[3]

[1]*Poldanor SA, ul. Dworcowa 25, 77-320 Przechlewo*
[2]*Katedra Chemii Rolnej i Biogeochemii Środowiska, Uniwersytet Przyrodniczy w Poznaniu, ul. Wojska Polskiego 71F, 60-625 Poznań*
[3]*Katedra Metod Matematycznych i Statystycznych, Uniwersytet Przyrodniczy w Poznaniu, ul. Wojska Polskiego 71F, 60-637 Poznań*

Abstract. A field study was carried out on maize in 2007–2011, with the aim to determine the effect of differentiated phosphorus and potassium fertilization rates on N, P, and K contents in maize organs as well as accumulation of these nutrients at maize physiological maturity. A single-factor experiment was established in a randomized complete block design with 4 replications for each treatment. The obtained results showed that the experimental factor significantly varied macronutrient contents in the analyzed maize organs. Mineral fertilization significantly increased N concentration when compared to the control. Significant effects of the experimental factor on the differences between the treatments with regard to phosphorus and potassium contents were found, nonetheless, when compared to the control, nutrient increase was not observed in all the organs examined. An especially strong maize response to the absence of potassium fertilization or application of different rates of this element was observed in maize stems, leaves and husks. The form of phosphorus applied as fertilizer showed no significant effect on P contents in the maize organs, as well as on the total accumulation of this nutrient in the plant. Percentage shares of grain accumulated nutrients in the total nutrient accumulation in the aboveground biomass showed significant differentiation as a result of P and K fertilization. For the most part, nitrogen and phosphorus were accumulated in maize grain (60–70%), and potassium – in the stems (50–61%). Regardless of the treatment examined, regression analysis showed that maize yields were determined by the total accumulation of nitrogen.

Key words: maize, nutrient harvest index, nutrient uptake, physiological maturity

INTRODUCTION

During the last decade, maize has turned out to be a crop plant cultivated in Poland on dynamically expended areas. An enhanced interest in maize cultivation is associated with utilization of this crop as renewable energy resource, among others – in biofuel production. Maize is characteristic of a very high yield potential, expressed both by plant biomass and grain yields [Potarzycki 2010a]. Among the factors limiting the amount of possibly obtainable yield, there are frequently highlighted those with regard to plant specific requirements, such as water accessibility and mineral nutrient imbalance. Maladjustment of the fertilization system to plant quantitative needs, and especially to nutrient uptake dynamics in grain-field crops, results in disturbances in the functions of individual nutrients, low rates of their utilization by plants as well as an increased risk of environment pollution [Öborn et al. 2005, Roberts 2008]. The fulfillment

[2] *Corresponding address* – Adres do korespondencji: grenata@up.poznan.pl

of the fundamental goal of maize fertilization, i.e. obtaining high and stable yields, requires a suitable supply of P and K at every growth stage of the plant, maintained at a level with no impedimental effects. Optimization of maize nutrition is essential to maintain the production of high quality yield [Zhang et al. 2007]. The tools to diagnose crop P status have become ever more important to minimize the risk of surface and groundwater contamination, owing to excessive fertilization on the one hand, and on the other – application of ample P rates for the best possible yield [Iho and Laukkanen 2012]. In many prosperous countries, phosphorus overload as a result of excessive use of fertilizers is perceived as an acuter environmental problem than those concerning P constraints and greater than ever costs of phosphorus fertilization [Abel et al. 2002]. In support of the maximum crop response, phosphorus needs adequate potassium levels as well as prospective P–K interactions in plant uptake [Çelik et al. 2010]. [Smil 1999] points out that in contrast to nitrogen and phosphorus, potassium fertilizers are applied at much lower rates, and less than 50% of potassium removed by crops is replenished. The effect of phosphorus and potassium on yields largely stems from the functions of these elements in lessening the influence of biotic and abiotic stress factors. The plants well nourished with P and K better withstand water deficit and low temperatures, and are more resistant to pathogenic agents [Ma et al. 2006, Zörb et al. 2014]. During plant growth, efficient water management is conditioned by adequate nutrition with potassium. Physiological analyses showed, that inhibition of plant growth (precisely, that of plant somatic cells) was the first, direct symptom of unsatisfactory potassium supply. Visible signs of K deficiency are reflected in undersized plants in grain-fields, often with leaf chlorosis. Recent studies have shown higher K contents in chlorotic plant parts [Çelik et al. 2010, Torres et al. 2006]. The status observed is not just the effect of direct potassium action, because an additional stress factor is indirectly involved in the process, i.e. insufficient supply of nitrogen and iron. Plant functioning depends on balanced fertilization with all macro- and micronutrients. The nutrients hardly ever act separately. Nutrient interactions can have both of synergistic and antagonistic character. The interactions can either enhance or reduce nutrient uptake and utilization. Numerous studies showed, that the interaction between nitrogen and other nutrients in the first place affect plant yields and nitrogen utilization [Fixen et al. 2005, Roberts 2008]. Leigh and Wyn [1984] reported that adequate K supply is needed to maintain N metabolism.

Up to date knowledge on maize response to phosphorus and potassium supply allows to assume the following hypothesis: the accumulation of nitrogen (N), phosphorus (P) and potassium (K) by maize specifies a changeable reaction to pre-seeding fertilization with phosphorus and potassium. The aim of the present study was to assess nutrient contents in maize organs as well as their accumulation in this crop at the stage of physiological maturity, under differentiated rates of mineral fertilization with P and K.

MATERIAL AND METHODS

During 5 subsequent vegetation seasons (2007–2011), in the Wieszczyczyna agricultural holding, situated in close proximity to the Śrem city (central Poland, 52°02′ N, 17°05′ E), there was conducted an exact field experiment on 'Veritis' maize variety. The single-factor experiment was established in the randomized complete block design with 4 replications for each treatment. The experiment was a part of the long-term study undertaken in 2000. The soil with acidic reaction (pH KCL 4.9) was characterized by medium contents of available phosphorus, potassium and magnesium. The experimental factor tested was the differentiated rate of mineral fertilization with phosphorus and potassium. The doses of phosphorus and potassium were adjusted to 25% (W25) and 50% (WP50, WK50) with reference to the treatment with optimally balanced nitrogen (W100). The level of P fertilization in the latter was 26 kg P·ha^{-1}, with the exception of the year 2007, when 35 kg P·ha^{-1} was applied. Depending on the observation year, potassium rates ranged from 100 kg K·ha^{-1} (2007) to 133 kg K·ha^{-1} (2009). During the other vegetation seasons observed, there was applied 125 kg K·ha^{-1}. The control treatments were fertilized with constant nitrogen and magnesium rates, and there was neglected fertilization with P (WPN) or K (WKN). In W100-PAPR treatment, there was applied partially acidulated phosphate rock as an alternate source of phosphorus in single superphosphate. Phosphate rock used in the study contained 10.2% of P and its acidification was 50% (i.e. sulfuric acid amount utilized during the technological process for obtaining the product was 50% of the amount necessary for the production of single superphosphate). All other treatments were fertilized with phosphorus in the form of single superphosphate, potassium as potassium salt (60% K_2O) and nitrogen as ammonium nitrate. The source of magnesium was kieserite (27% MgO), applied at a rate 16 kg Mg·ha^{-1}. Depending on the observation year, nitrogen was added at a rate 120 kg N·ha^{-1} or 150 kg N·ha^{-1}, and these were split into 2 doses (70% before plant seeding and 30% at the stage of 4 fully unfolded leaves). Detailed description of methodology is presented by Bąk and Gaj [2016].

Plant yield and N, P and K concentrations were assessed every year study of the study. Maize grain yield was determined in plants harvested manually from two adjacent central rows (16 m long). Details on maize yields obtained are provided in the paper by Bąk and Gaj [2016]. During nutrient concentration assessments, 5 maize plants were randomly chosen (on each treatment) and divided into the sets of leaves, stems, husks, grain and cob cores. Plant samples were dried out at 65ºC to the constant weight and ground for further analyses. Nitrogen concentration in the plant material was determined by the Kjeldahl method (Auto Distillation unit Kjeltec 2200 FOSS). P and K concentrations were assessed in ground plant material and mineralized at 550ºC for 6 hours. Next, the ash obtained was mixed with 2cm^3 of diluted HNO_3 (concentrated nitric acid and distilled water 1:1). Phosphorus was determined calorimetrically with vanadium-ammonium molybdate. Potassium concentration was assessed by the FAAS method (Flame Atmomic Absorption Spectrophotometry, Varian 250 plus). Nutrient uptake was calculated based on dry weight values multiplied by nutrient concentration in plant organs (information on dry weights available from the authors). Nutrient harvest indexes (NHI, PHI, KHI) were calculated based on the algorithms concerning relations between nutrient accumulation in maize grain and the total nutrient accumulation in maize plant at the stage of physiological maturity. Unit nutrient uptake has been calculated by dividing total amount uptake of N, P and K respectively by grain yield of maize.

The effect of the experimental factor on nutrient accumulation and concentration under differentiated mineral fertilization with P and K was tested with 2-way ANOVA (mixed-effects model).

The symbol y_{ij} expressed the estimated value of the variables (concentration of nutrients examined in plant organs, nutrient accumulation and the specific rate of nutrient uptake) coming from analyzed i-observation year (i =1,…,5) at j different fertilization treatments (j = 1,…,8) [Caliński et al. 1987].

The mixed-effects model in 2-way ANOVA including interactions of the factors was as follows for random factor A and constant factor B:

$$y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_k + e_j$$

where:
μ – grand mean
α_i – is the effect of i-th year

$ß_i$ – is j-th fertilization treatments
$(\alpha ß)_{ij}$ – A and B interaction effect at $\alpha_i ß_j$

The Tukey's test (multiple comparison procedure) was used for comparing mean macronutrient concentrations under different fertilization treatments and splitting up the set of mean values into homogenous groups [Kala 2002].

When independent (predictor) variables are correlated, a one step procedure is of no use in determination of independent variables that should be included in the regression model. This means, that it is necessary to apply another method allowing to establish the best set of independent variables. Cause-result relationships between the parameters analyzed were tested by means of multiple regression. The regression model was built based on stepwise regression with bidirectional elimination, testing at each step for variables to be included or excluded. In this way, crucial variables deciding about the yield obtained were determined.

The goal of stepwise regression is to include the minimum set of independent variables in the model, and at the same time, to maximize the determination coefficient and to minimize mean squared error in regression analysis.

RESULTS AND DISCUSSION

At maize physiological maturity, nutrient concentrations were analyzed in maize grain, stems, leaves, husks and cob cores. The concentrations of nitrogen, phosphorus and potassium in these organs analyzed were significantly differentiated as a result of different P and K fertilization rates, depending on the nutrient and organ analyzed (Table 1 and 2). The fertilization treatments applied to maize had no definite effect on the concentration of the nutrients observed.

Table 1. Effect of experimental factor on nutrient concentration in maize ear (grain, cob core, husks) $g \cdot kg^{-1}$ D.M. (mean 2007–2011)

Treatments	Maize parts								
	Grain			Husk leaves			Cob core		
	N	P	K	N	P	K	N	P	K
Control*	13.4 c	2.32 ab	3.54 ab	4.96 a	0.72 a	5.80 ab	5.52 a	0.41 a	9.24 a
WPN	15.3 ab	2.33 ab	3.75 a	1.25 a	0.66 a	7.14 a	5.73 a	0.34 a	8.04 a
WKN	15.1 ab	2.36 ab	3.47 ab	4.93 a	0.63 a	5.18 b	5.54 a	0.41 a	9.17 a
W25	15.3 ab	2.49 a	3.70 a	5.12 a	0.67 a	6.13 ab	5.79 a	0.33 a	7.83 a
WP50	15.7 a	2.25 ab	3.68 a	5.19 a	0.79 a	6.56 a	5.71 a	0.32 a	9.09 a
WK50	15.7 a	2.25 b	3.28 b	5.32 a	0.64 a	5.95 ab	5.60 a	0.32 a	9.39 a
W100	15.5 a	2.29 ab	3.53 ab	5.08 a	0.88 a	6.06 ab	5.30 a	0.35 a	8.45 a
W100 P as PAPR	14.2 bc	2.25 b	3.47 ab	4.97 a	0.61 a	6.16 ab	5.89 a	0.40 a	7.96 a

*Control – no fertilizer application in 2007–2011; WPN – no phosphorus fertilization, optimal fertilization N, K, Mg; WKN – no potassium fertilization, optimal fertilization (N, P, Mg); W25 – 25% of PK recommended rate as compared to optimally fertilized treatment; WP50 and WK50 – 50% of P or K respectively recommended rate as compared to optimally fertilized treatment; W100 – 100% of P and K recommended rate, treatment optimally balanced with regard to nitrogen; W100 PAPR – phosphorus applied as partially acidulated phosphate rock (PAPR)

Table 2. Effect of experimental factor on nutrients concentration in vegetative maize parts, g·kg^{-1} (mean 2007–2011)

Treatments	Maize parts					
	Stem			Leaves		
	N	P	K	N	P	K
Control	5.55 a	1.31 c	22.6 bc	9.75 c	1.52 a	4.55 b
WPN	5.73 a	1.66 abc	26.6 ab	12.2 a	1.31 a	6.54 a
WKN	5.78 a	1.54 abc	18.5 d	11.9 ab	1.32 a	4.74 b
W25	5.78 a	1.42 bc	21.7 cd	12.4 a	1.33 a	5.80 ab
WP50	5.71 a	1.44 bc	26.3 ab	10.4 bc	1.38 a	5.67 ab
WK50	6.18 a	1.96 a	25.9 ab	10.3 bc	1.51 a	5.67 ab
W100	5.59 a	1.80 ab	27.8 a	11.2 abc	1.43 a	5.93 ab
W100 P as PAPR	6.03 a	1.64 abc	24.4 abc	11.7 ab	1.64 a	6.54 a

Treatments – explanation as in Table 1

Mineral fertilization resulted in an increase of nitrogen observed in all the organs analyzed when compared to the control. Significant differences in N concentrations in maize grain and leaves were observed between the fertilized treatments. Maize grain and leaves showed the highest N contents and considerable differentiation owing to the influence of the experimental factor. Regardless of the treatment applied, N concentration in maize grain was above the threshold value (12.6 g·kg^{-1}) determined by Liang et al. [1996]. In other plant organs examined (stems, husks, cob cores), N concentrations were comparable, with an increasing trend observed in all the fertilized treatments when compared to the control.

Phosphorus concentration in the maize organs analyzed was decreasing in the following order: grain> stems > leaves> husks>cob cores. Significant differences in P concentrations as a result of the effect of the experimental factor were observed in maize grain and stems. Regardless of the organ analyzed, no significant differences were observed in P concentration dependant on the form of phosphorus used in fertilizer applied. Differentiated fertilizer rates had no conclusive effect on differences in phosphorus concentrations in the organs analyzed with respect to the treatments applied. The concentration of phosphorus in maize grain was differentiated depending on both P and K rate applied and ranged narrowly from 2.24 to 2.48 g·kg^{-1}. In maize grain, when compared to the control, the highest increase of P concentration was observed only in the treatment with the minimal phosphorus and potassium rates (W25). Analogous relationships between phosphorus fertilization and its contents in grain was observed in wheat [Gaj and Górski 2014, Gaj and Rębarz 2014] as well as in maize [Bêlanger et al. 2011, 2012]. Up to date, numerous studies have been carried out on P concentration in corn kernels, however information on the critical concentration of this nutrient has been so far unavailable. Furthermore, no study results on P concentrations concerning the whole plant intended for fodder valuation have been published [Gautam et al. 2011]. Numerous studies indicate weak yield-forming response of maize to phosphorus fertilization as well as no relationship between P fertilization and plant P concentration [Al-Kaisi and Kwaw-Mensah 2007, Olczyk et al. 2003]. This implies a strong need to adjust fertilizer rates for soils with high P availability, bearing in mind other factors with decisive effects on plant needs with regard to phosphorus, such as weather course in the vegetation season, plant growth environment and agricultural techniques [Gaj 2008]. Studies by Kamara et al. [2008] showed no significant relationships between phosphorus rates applied and its concentration in soybeans, however, significant differences were found in maize cultivated after soybeans in the same sites. Carsky et al. [2000] reported that P application significantly increased soybean root dry matter and root length density, which might improve soil structure, and consequently enhance water and nutrient utilization by maize and higher grain yield. In the present study, P concentration in the stems was the highest in WK50 treatment – significantly different from the control as well as W25 and WP50.

Sufficient supply of other nutrients to plants is another essential factor decisive of the concentration of a given nutrient in the plant. The ratio of N and P could be used for a posteriori diagnostics of P and N deficiencies to adjust maize crop fertilization. The nutritional status of plant with regard to nitrogen decides about phosphorus uptake. What is more, these two nutrients are involved in the processes of photosynthesis, protein biosynthesis and N_2 bonding. In the present study, N: P ratio in maize grain was significantly differentiated under the influence of the experimental factor and ranged from 5.89 (control) to 7.18 (WP50) (Table 3). Bêlanger et al. [2012] points out that grain N: P ratio below 4.0 increases the risk of maize yield reduction. Correlation analysis performed in this study proved a significant relationship between maize yield and N:P ratio in grain (0.589). Greenwood et al. [2008] and Sadras [2006] showed a significant N:P ratio increase only when grain concentrations of N and P were divergently affected by N fertilization. Sadras [2006] studied N:P ratio in cereals and showed that in more than 40% of the maximum yield plants, N:P ratio ranged narrowly, from 4.0 to 6.0. Interactions between nitrogen and phosphorus have been described in numerous studies [Sadras 2006, Skowrońska and Filipek 2010, Ziadi et al. 2007]. Rychter and Randall [1994] underline that prolonged phosphorus deficiency in the plant reduces the pool of ATP and other high energy compounds, and as a result, there decreases uptake of nitrate nitrogen ($N\text{-}NO_3$). On the other hand, nitrogen excess at phosphorus shortage causes the first symptom of P deficiency. Regarding field conditions, there still remains an important question on N and P interactions and the improvement of nutrient utilization by plants. There should be also taken into account that nitrogen-phosphorus

Table 3. Effect of experimental factor on nutrients harvest index (HI) and unit nutrients uptake (mean 2007–2011)

Treatments	Unit uptake of nutrients*, $kg \cdot t^{-1}$			Nutrient harvest index (%)			N/P
	N	P	K	NHI	PHI	KHI	
Control	19.8 b	3.41 a	16.7 bc	67.6 bc	68.2 ab	22.4 bc	5.89 c
WPN	22.4 a	3.62 a	19.1 a	68.1 abc	66.1 abc	20.7 c	6.67 abc
WKN	22.2 a	3.51 a	14.8 c	68.6 abc	68.0 ab	27.2 a	6.57 abc
W25	21.8 a	3.53 a	15.2 c	70.0 ab	71.2 a	25.7 ab	6.22 bc
WP50	22.3 a	3.39 a	18.1 ab	70.1 ab	67.0 abc	19.9 c	7.19 a
WK50	22.6 a	3.75 a	18.8 ab	69.1 abc	61.4 c	20.9 c	7.03 ab
W100	21.8 a	3.56 a	18.5 ab	71.3 a	64.9 bc	20.3 c	6.90 ab
W100 P as PAPR	21.5 a	3.57 a	17.9 ab	66.4 c	63.5 bc	20.5 c	6.36 abc

Treatments – explanation as in Table 1
* kg per 1t of grain, including concomitant amount of nutrient in vegetative parts, $kg \cdot t^{-1}$

interaction processes are influenced to a great extent by soil and climatic conditions [Summer and Farina 1986].

Potassium concentration in maize differed depending on the organ analyzed and decreased with the following order: stems> cob cores> husks > leaves> grain. Significant differences were observed in K concentration in plant organs as the effect of the experimental factor. Especially strong response of maize to no K fertilization (WKN) and differentiated rates of K applied was reflected in the stems and leaves (Table 1 and 2). Potassium concentration in grain showed a stronger relationship with phosphorus fertilization than that with potassium fertilization. The highest K content in maize grain was found in no P fertilization treatment (WPN). The lack of any relationship between increasing K contents in the soil and the concentration of this nutrient in maize grain was also observed by other authors [Bruns and Eberhard 2006]. According to Leigh and Johnston [1983], low nutrient content in the plant is a poor indicator of soil potassium availability. Askegaard et al. [2004] emphasizes that complementary to soil tests evaluation of potassium in plants is a key element of effective management of this nutrient. Both, deficiency and excess of mineral elements in cereal grains decrease their biological value, and as a consequence can negatively affect metabolic processes in animals and humans [Gondek 2012]. Every process or agricultural technique with disturbing effects on plant nutrition with potassium decreases plant metabolic activity, and at the same time – adds to the reduction of nitrogen efficiency. Vyn et al. [2002] point out that potassium contents in maize organs are significantly differentiated by cultivation techniques and potassium application mode.

The total accumulation of nitrogen, phosphorus and potassium was significantly differentiated by the experimental factor (Fig. 1–3). The lowest values of uptake of the analyzed nutrients were found in the control treatment. Regardless of the treatment applied, there was observed a significant increase of nutrient accumulation as the effect of mineral fertilization. The total nitrogen uptake in fertilized treatments ranged from 161 kg $N \cdot ha^{-1}$ to 179.2 kg $N \cdot ha^{-1}$. A consid-

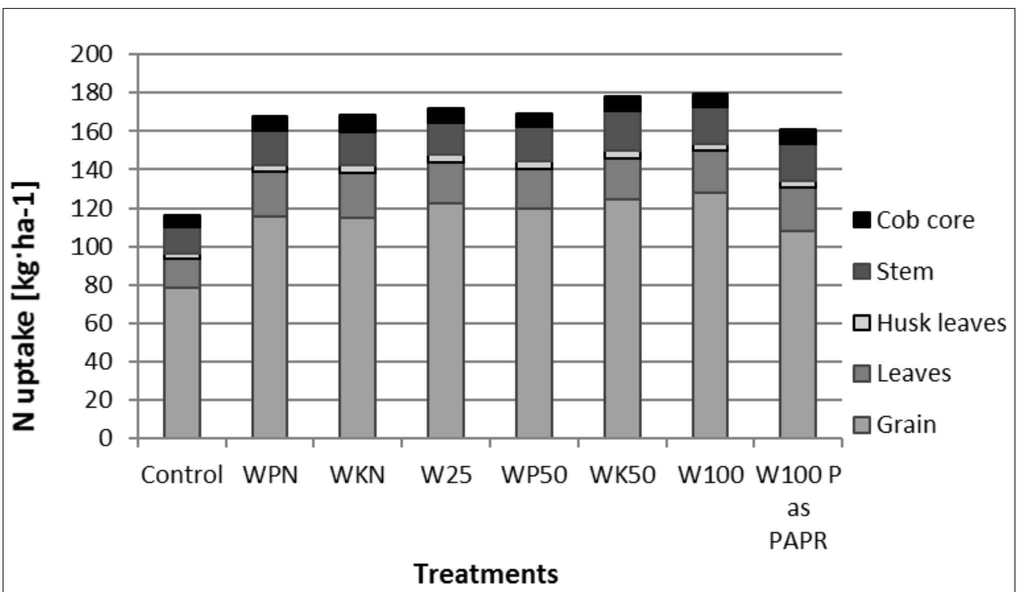


Fig. 1. Structure of nitrogen accumulation in maize at physiological maturity (BBCH 87) (mean 2007–2011)

erable portion of nitrogen taken by maize was accumulated in grain (Fig. 1). Percentage share of nitrogen accumulated in maize grain in the total accumulation of this nutrient in aboveground biomass is defined in subject literature as the nitrogen harvest index NHI. In the present study, NHI values ranged from 66 to 71% and significantly differed, depending on P and K fertilization levels (Table 3). At the same time, significant differences in NIH values were observed with reference to the source of phosphorus applied. Application of PAPR (W100 PAPR) resulted in significantly lower accumulation of phosphorus in maize grain when compared to that in the treatment with single superphosphate (W100). Yield size is shaped by the amount of phosphorus accumulated in the plant during the vegetation season and its distribution between plant organs. Yield diagnostics is based on the assessment of the final N accumulation in the plant and the index of N distribution between harvested and other plant organs [Sinclair 1998]. This was confirmed by correlation analysis performed in this study, with regard to the relationships between leaf and grain N concentrations, which showed highly significant relationships in all the treatments tested (0.867). In the period of maize generative development, the basic source of nitrogen is its stock earlier accumulated in the plant (mainly in the leaves and stems). Next, nitrogen compounds are hydrolyzed and translocated into maize grains [Grzebisz 2012]. The optimal growth conditions for grain-field crops are secured by adequate availability of nitrogen during their vegetative growth.

Accumulation of phosphorus as plant response to increasing P in fertilizer rates was significantly different in W100, WK50 and WP50 treatments (Fig. 2). Other experimental treatments did not significantly differed from each other. Phosphorus harvest index (PHI) value was the lowest in WK50 treatment, and significantly differed from other treatments examined. The highest PHI value was found in W25 treatment. Accumulation of phosphorus in grain increased with decreasing P rate in the fertilizer applied. High efficiency of P fertilization depends not only on phosphate uptake from the soil, but also on nutrient translocation between plant organs [Sattel-

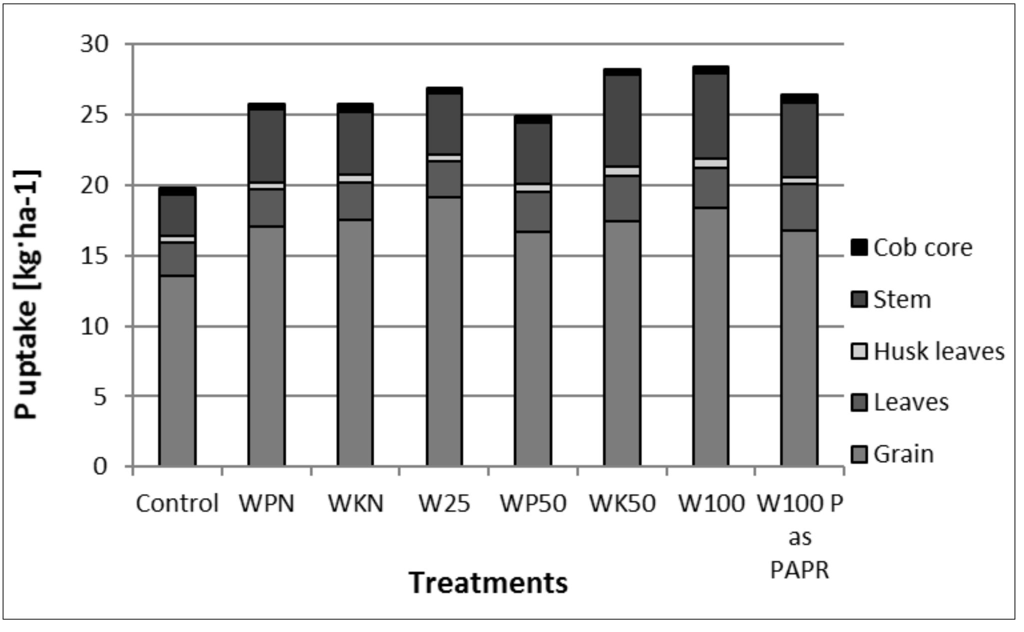


Fig. 2. Structure of phosphorus accumulation in maize at physiological maturity (BBCH 87) (mean 2007–2011)

macher et al. 1994]. High nutrient accumulation in grain indicates strong relationships between plant nutritional status and the amount of harvested yield. Application of PAPR as an alternate P source (W100 PAPR) had no effect on the total P accumulation in maize when compared to the treatment with single superphosphate (W100). Only a decreasing tendency in the total P uptake was observed as a result of PAPR application, which was 7% when compared to W 100 treatment.

In contrast to nitrogen and phosphorus, the majority of potassium was accumulated in maize stems (Fig. 3). Potassium harvest index (KHI) ranged from 20–27%, depending on the treatment (Table 3). The highest K accumulation in grain was observed in the treatment with no potassium fertilizer (WKN) for 10 years. Neglecting P or K fertilization resulted in much lower reduction of nitrogen and phosphorus accumulation in grain than that observed in the case of potassium. When compared to the treatment with the optimal fertilization level (W100), outstanding reduction of potassium uptake (26%) was observed in WKN treatment. The difference between K uptake in the control treatment when compared to that in WKN was 13%. Similar relationships with regard to K accumulation in maize under differentiated NPK fertilization were reported by other authors [Paramasivan et al. 2011].

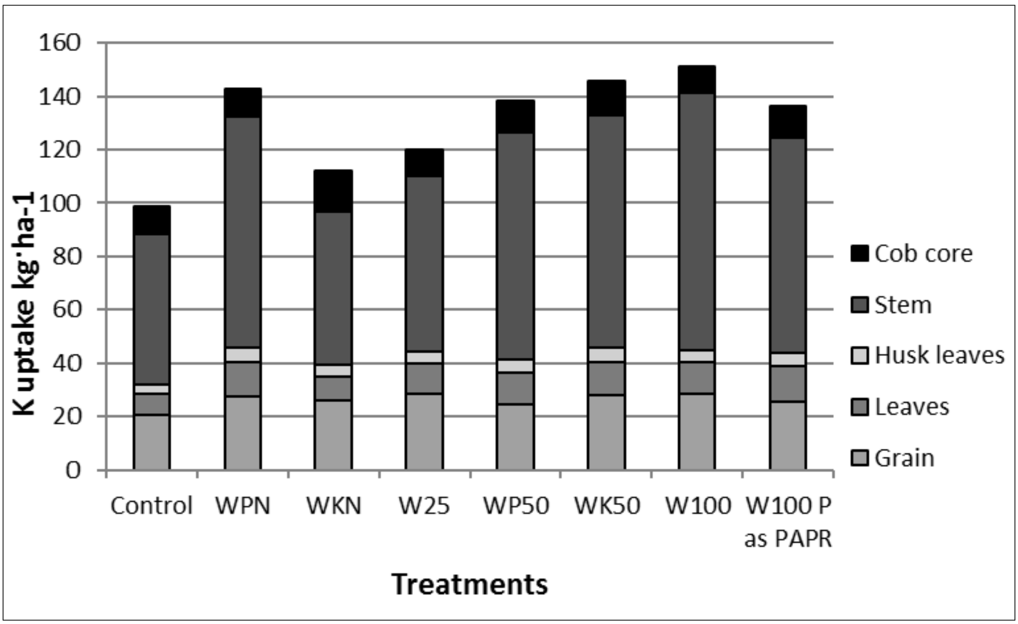


Fig. 3. Structure of potassium accumulation in maize at physiological maturity (BBCH 87) (mean 2007–2011)

Regardless of the treatment applied, regression analysis showed that maize grain yield was determined to the largest extent by the total accumulation of nitrogen (Table 4), exclusive of W100 treatment and the absolute control. In the two latter treatments, there were found significant relationships between yield and the total N, P and K accumulation (W100) as well that of N and K (control).

Stepwise regression analysis including relationship between yield and nutrient accumulation in individual organs (grain, stems, leaves, husks, cob cores) and specific nutrient uptake,

Table 4. Regression models of maize grain yield as the function of nutrient uptake at physiological maturity of maize

Treatments	Regression models	R^2
Control	y = 0.0222N + 0.0516P + 0.0069K + 1.5476 (***) (*) (***)	0.934
WPN	y = 0.0204N + 0.0506P + 0.0058K + 2.2014 (***) (*)	0.874
WKN	y = 0.0190N + 0.0303P + 0.0025K + 3.4422 (***) (**)	0.910
W25	y = 0.0256N +0.0101P - 0.0005K + 2.9148 (***) (***)	0.919
WP50	y = 0.0279N + 0.0151P - 0.0002K + 2.2946 (***) (***)	0.950
WK50	y = 0.0176N + 0.0090P + 0.0112K + 2.8776 (**)	0.790
W100	y = 0.0147N + 0.1088P + 0.0076K + 1.2276 (***) (**) (*)	0.887
W100 P as PAPR	y = 0.0192N + 0.1676P - 0.0012K + 0.1140 (***) (**)	0.825

Treatments – explanation as in Table 1
Significat at: 0‘***’, 0.001‘**’, 0.01‘*’

showed differentiation depending on the treatment. The relationships are presented in table 4. In each of the treatments analyzed, grain yield was determined to the biggest extent by nitrogen accumulation in grain, and then by accumulation of other nutrients examined in the present study. One exception was W25 treatment, which showed the relationship of maize yield only with N accumulation in grain, as described by the presented equation: y (yield) = 0.06UG + 4.99, R^2 = 0,919; where: UG – accumulation N in grain.

The specific rate of nutrient uptake provides information on nutrient amount per unit of harvested yield. The analysis of experimental factor action showed that it significantly differentiated potassium uptake. Significant differences in N uptake were shown only when compared to the control treatment (Table 3). With regard to the specific rate of P uptake, an increasing tendency was observed as a result of mineral fertilization (not including WP50 treatment). The values obtained for the indexes analyzed in the present study were lower in comparison to those reported by other authors [Potarzycki 2010b, Wrońska et al. 2007]. Considerably large differences were observed in the case of nitrogen. In the present study, the specific rate of nitrogen uptake was on average 21 kg $N \cdot t^{-1}$, whereas that reported by Potarzycki [2010b] was at a level 30 kg $N \cdot t^{-1}$. The success of effective production of maize grain relies upon the reduction of plant uptake of nitrogen per yield unit, and this is possible under the conditions of appropriate plant nutrition with other nutrients.

CONCLUSIONS

1. Nitrogen, phosphorus and potassium concentrations in maize organs at the stage of physiological maturity were depended on analyzed organ and were significantly differentiated by the experimental factor.
2. When compared to the control treatment, differentiated P and K fertilization rates significantly increased nitrogen concentration in maize organs (with the exception of stems), on the other hand, they ambiguously affected the differences in P and K concentrations observed between the treatments tested.
3. The form of phosphorus applied as fertilizer had no significant effect on P concentration in maize organs as well as on the total accumulation of phosphorus in the plant.
4. The percentage share of nutrients accumulated in maize grain in the total nutrient accumulation in aboveground biomass showed significant differentiation under P and K fertilization. Nitrogen and phosphorus were accumulated for the most part in maize grain 60–70%), whereas potassium – in maize stems (50–61%).
5. Regardless of the treatment examined, regression analysis showed that maize grain yield was determined to the largest extent by the total accumulation of nitrogen in the plant.

REFERENCES

Abel S., Ticconi C., Delatorre C.A. 2002. Phosphate sensing in higher plants. Physiol. Plant.115: 1–8.

Al-Kaisi M., Kwaw-Mensah D. 2007. Effect of tillage and nitrogen rate on corn yield and nitrogen and phosphorus uptake in corn-soybean rotation. Agron. J. 99: 1548–1558.

Askegaard M., Eriksen J., Johnston A.E. 2004. Sustainable management of potassium. In: Managing soil quality – challenges in modern agriculture. Schjonning P., Elmholt S., Christensen B.T. (Eds.). CAB International, Wallingford UK: 85–102.

Bąk K., Gaj R. 2016. The effect of differentiated phosphorus and potassium fertilization on maize grain yield and plant nutritional status at the critical growth stage. J. Elementol. 21: 337–348.

Bêlanger G., Claessens A., Ziadi N. 2011. Relationships between P and N concentrations in maize and wheat leaves. Field Crops Res. 123: 28–37.

Bêlanger G., Claessens A., Ziadi N. 2012. Grain N and P relationships in maize. Field Crops Res. 126: 1–7.

Bruns A., Ebelhar M.W. 2006. Nutrient uptake of maize affected by nitrogen and potassium fertility in a humid subtropical environment. Comm. Soil Sci. Plant Anal. 37: 275–293.

Caliński T., Czajka S., Kaczmarek Z. 1987. A model for the analysis of a series of experiments repeated at several places over a period of years. I. Theory. Biul. Oceny Odmian 17-18: 7–33.

Carsky R.J., Berner D.K., Oywole D., Dashiell K. 2000. Reduction of *Striga hermonthica* parasitism on maize using soybean rotation. Int. J. Pest Manage. 46: 115–120.

Çelik H., Bülent B., Gürel S., Katkat A. 2010. Effects of potassium and iron on macro element uptake of maize. Zemdirbyste 97(1): 11–22.

Fixen P.E., Jin J., Tiwari K.N., Stauffer M.D. 2005. Capitalizing on multi-element interactions through balanced nutrition – a pathway to improve nitrogen use efficiency in China, India and North America. Sci. China, Ser. C Life Sci. 48: 1–11.

Gaj R. 2008. Sustainable management of phosphorus in soil and plants in condition of intensive plant production. Naw. Nawoż./Fert. Fertil. 33:143.
Gaj R., Górski D. 2014. Effects of different phosphorus and potassium fertilization on contents and uptake of macronutrients (N, P, K, Ca, Mg) in winter wheat. I. Content of macronutrients. J. Cent. Europ. Agric. 15(4): 169–187.
Gaj R., Rębarz K. 2014. Effects of different phosphorus and potassium fertilization on contents and uptake of macronutrients (N, P, K, Ca, Mg) in winter wheat. II. Uptake of macronutrients. J. Cent. Europ. Agric. 15(4): 188–198.
Gautam P., Gustafson D.M., Wicks Z. 2011. Phosphorus concentration, uptake and dry matter yield of corn hybrids. World J. Agric. Sci. 7(4): 418–424.
Gondek K. 2012. Effect of fertilization with farmyard manure, municipal sewage sludge and the compost from biodegradable waste on yield and mineral composition of spring wheat grain. J. Elementol. 2: 231–245.
Greenwood D.J., Karpinets T.V., Zang K., Bosh-Serra S., Boldrini A., Karawulova L. 2008. A unifying concept for the dependence of whole-crop N:P ratio on bimass: theory and experiment. Ann. Bot. 102: 967–977.
Grzebisz W. 2012. Technologie nawożenia roślin uprawnych – fizjologia plonowania. T. 2. Zboża i kukurydza. Wyd. PWRiL.
Iho A., Laukkanen M. 2012. Precision phosphorus management and agricultural phosphorus loading. Ecol. Econ. 77: 91–102.
Kala R. 2002. Statystyka dla przyrodników. Wyd. AR Poznań, 231.
Kamara A.Y., Kwari J., Ekeleme F., Omoigui L., Abaidoo R. 2008. Effect of phosphorus application and soyebean cultivar on grain and dry matter yield of subsequent maize in the tropical savannas of north-eastern Nigeria. African J. Biotechnol. 7: 2593–2599.
Leigh R.A., Johnson A.E. 1983. Concentrations of potassium in the dry matter and tissue of field-grown spring barley and their relationships to grain yield. J. Agric. Sci. 101: 675–685.
Leigh R.A., Wyn Jones R.G. 1984. A hypothesis relating critical potassium concentration for growth to the distribution and function of this ion in the plant cell. New Phytol. 97: 1–13.
Liang B.C., MacKenzie A.F., Zhang T.Q. 1996. Grain yields and grain nitrogen concentration of corn as influenced by fertilizer nitrogen rate. J. Agron. Crop Sci. 177: 217–223.
Ma Q., Niknam S.R., Turner D.W. 2006. Responses of osmotic adjustment and seed yield of *Brassica napus* and *B. junacea* to soil water deficit at different growth stages. Aust. J. Agric. Res. 57: 221–226.
Öborn I., Andrist-Randel Y., Askekaard M., Grant C.A., Watson C.A., Edwards A.C. 2005. Critical aspects of potassium management in agricultural systems. Soil Use Manage. 21: 102–112.
Olczyk T., Li Y., Simonne E., Mylavarapu R. 2003. Reduced phosphorus fertilization effects on yield and quality of sweet corn grown on a calcareous soil. Proceed. Fla. State Hort. Soc. 116: 95–97.
Paramasivan M., Kumaresan K.R., Malrvizhi P., Velayudham K. 2011. Effect of different levels of NPK and Zn on yield and nutrient uptake by hybrid maize (COHM 5) in Pilamedu and Palaviduthi series of Tamil Nadu. Madras Agric. J. 98: 334–338.
Potarzycki J. 2010a. Improving nitrogen use efficiency of maize by better fertilizing practices. Naw. Nawoż./Fert. Fertil. 39: 5–24.
Potarzycki J. 2010b. Effect of increased input of fertilizers balancing nitrogen on nutrients accumulation by maize at maturity. Naw. Nawoż./Fert. Fertil. 39: 60–77.
Roberts T.L. 2008. Improving nutrient use efficiency. Turk J. Agric For. 32: 177–182.
Rychter A.M. Randall D.D. 1994. The effect of phosphate deficiency on carbohydrate metabolism in bean roots. Physiol. Plant. 91: 383–388.
Sadras V.O. 2006. The N: P stoichiometry of cereal, grain legume and oilseed crops. Field Crops Res. 95: 13–29.
Sattelmacher B. Horst W.J., Becker H.C. 1994. Factors that contribute to genetic variation for nutrient efficiency of crop plants. Z. Pflanzenernähr. Bodenkd. 157: 215–224.
Sinclair T. 1998. Limits to crop yield. NAS colloquium: Plants and population: is there time? 5–6 December 1998 (www.1sc.psu.edu/nas/Panelisy)
Skowrońska A., Filipek T. 2010. Accumulation of nitrogen and phosphorus by maize as the result of a reduction in the potassium fertilization rate. Ecol. Chem. Eng. S. 17: 83–88.

Smil V. 1999. Crop residues: agriculture's largest harvest. Bioscience 49: 299–308.
Summer M.E. Farina M.P. 1986. Phosphorus interactions with other nutrients and lime in field cropping systems. Adv. Agric. Sci. 5: 201–236.
Torres R.M., Barra J.D.E., Gonzales G.A. 2006. Morphological changes in leaves of Mexican lime affected by iron chlorosis. J. Plant Nutrition 25: 615–628.
Vyn T.J., Galic D.M., Janovicek K.J. 2002. Corn response to potassium placement in conservation tillage. Soil Tillage Res. 67: 159–169.
Wrońska M., Grzebisz W., Potarzycki J. Gaj R. 2007. Maize response to nitrogen and zinc fertilization. Part II. Accumulation of nutrients at maturity. Fragm. Agron. 24(2): 400–407 (in Polish).
Zhang K., Greenwood D.J., White P.J., Burns I.G. 2007. A dynamic model for the combined effects of N, P and K fertilizers on yield and mineral composition; description and experimental test. Plant Soil 298: 81–98.
Zidai N., Bêlanger G., Cambouris A.N., Trmblay N., Nolin M.C., Claessens A. 2007. Relationship between P and N concentration in corn. Agron. J. 99: 833–841.
Zörb Ch., Senbayram M., Peiter E. 2014. Potassium in agriculture – Status and perspectives. J. Plant Physiol. 171: 656–669.

K. Bąk, R. Gaj, A. Budka

AKUMULACJA AZOTU, FOSFORU I POTASU PRZEZ KUKURYDZĘ W FAZIE DOJRZAŁOŚCI PEŁNEJ W WARUNKACH ZRÓŻNICOWANEGO NAWOŻENIA MINERALNEGO

Synopsis. W latach 2007–2011 przeprowadzono doświadczenie polowe z kukurydzą, którego celem było określenie wpływu zróżnicowanego nawożenia mineralnego fosforem i potasem na zawartość N, P i K w organach kukurydzy oraz akumulację tych składników w fazie dojrzałości fizjologicznej. Jednoczynnikowy eksperyment założono w układzie bloków losowych kompletnych w czterech powtórzeniach dla każdego obiektu. Przeprowadzone badania wykazały, że czynnik doświadczalny istotnie różnicował zawartość makroskładników w analizowanych organach. W przypadku zawartości azotu nawożenie mineralne P i K istotnie zwiększyło jego zawartość w porównaniu do wariantu kontrolnego. W odniesieniu do zawartości fosforu i potasu stwierdzono istotny wpływ czynnika doświadczalnego na kształtowanie różnic pomiędzy obiektami, ale nie w każdym przypadku zanotowano wzrost zawartości składników w analizowanych organach w porównaniu do obiektu kontrolnego. Szczególnie silna reakcja kukurydzy na brak nawożenia potasem oraz zmienne dawki tego składnika w nawozie uwidoczniła się w łodygach, a także w liściach i koszulkach. Forma fosforu aplikowanego w nawozie nie miała istotnego wpływu na zawartość P w analizowanych organach kukurydzy, a także całkowitą akumulację pierwiastka przez roślinę. Nagromadzenie analizowanych składników w ziarnie względem całkowitej akumulacji pierwiastków w biomasie nadziemnej wykazało istotne zróżnicowanie pod wpływem nawożenia P i K. Azot i fosfor zakumulowane były w większości w ziarnie kukurydzy (60–70%), natomiast potas w łodygach (50–61%). Niezależnie od analizowanego wariantu doświadczalnego analiza regresji wykazała, że plon ziarna kukurydzy w największym stopniu determinowany był przez całkowitą akumulację azotu.

Słowa kluczowe: kukurydza, indeks żniwny akumulacji składników, pobranie składników, dojrzałość fizjologiczna

Accepted for print – Zaakceptowano do druku: 4.03.2016

For citation – Do cytowania:
Bąk K., Gaj R., Budka A. 2016. Accumulation of nitrogen, phosphorus and potassium in mature maize under variable rates of mineral fertilization. Fragm. Agron. 33(1): 7–19.

A3

DOI: 10.1515/bile-2016-0002

DE GRUYTER OPEN

Biometrical Letters
Vol. 53 (2016), No. 1, 21-36

Copper and manganese acquisition in maize (*Zea mays* L) under different P and K fertilization

Renata Gaj[1], Krzysztof Bąk[2], Anna Budka[3]

[1]Katedra Chemii Rolnej i Biogeochemii Środowiska, Uniwersytet Przyrodniczy w Poznaniu, Wojska Polskiego 71F, 60-625 Poznań, Poland
[2]Poldanor SA, Dworcowa 25, 77-320 Przechlewo, Poland,
[3]Katedra Metod Matematycznych i Statystycznych, Uniwersytet Przyrodniczy w Poznaniu, Wojska Polskiego 28, 60-637 Poznań, Poland, email: abudka@up.poznan.pl

SUMMARY

The paper demonstrates the influence of different mineral fertilization with phosphorus and potassium on the concentration of copper (Cu) and manganese (Mn) in the ear leaf of maize at the stage of flowering (BBCH 65) as well as the contents and accumulation of the nutrients studied in maize when fully ripe (BBCH 89). A single factor experiment was carried out in 5-year-cycle (2007-2011), in the randomized complete block design. The experiment was conducted as a part of a long-term stationary trial. The investigation comprised 8 different P and K treatments: the absolute control, exclusive of one of the main nutrients (P - WPN or K - WKN), reduced amount of phosphorus and potassium (to 25% - W25 and to 50% WP50, WK50) as well as recommended amounts of basic nutrients (NPKMg - W100 and NP*KMg, P* - P* as PAPR - W100 PAPR). Evaluation of the nutriational status, performed in the ear leaf of maize at flowering stage, showed that regardless of fertilization treatment applied, the concentration of copper was lower than normative values, whereas that of manganese ranged within the optimal scope. At the same time, there was found a significant relationship between the grain yield obtained and acquisition of both copper and manganese by maize at flowering stage (stronger for manganese, r = 0.614). The total accumulation of copper and manganese in fully ripe maize was significantly differentiated as a result of mineral fertilization. The total uptake of Cu and Mn was reduced under the conditions of 10-year lack of P fertilization. Uptake reduction was considerably more advanced when K fertilization was absent for 10 years. Regardless of the experimental factor effects, more than 50% of the total copper uptake was accumulated in grain, whereas the majority of manganese was accumulated in maize leaves (50-64% of the total uptake). Correlation analysis showed a significant relationship between maize grain yield and the total accumulation of copper, whereas that of manganese was observed only in 3 of 8 treatments tested (WPN, WP50 and W100 as PAPR).

Key words: micronutrient uptake, grain harvest index, unit uptake

1. Introduction

As maize acreage has recently shown increasing tendency all over the world including Poland, there is a need to better understand requirements of this crop for not only macronutrients such as nitrogen, phosphorus, potassium, magnesium, calcium and zinc, but also - micronutrients, such as manganese and copper. Maize is a staple crop in many parts of the word, and is often targeted for micronutrient „biofortification" (Xia et al., 2013). Suitable micronutrient concentration in crop plants is not only a crucial issue in agricultural technology, but also a key quantitative indicator in the standards of food and fodder consumption (Fageria et al., 2008; Van Campen and Glahn, 1999). As said by Quzounidou et al. (1995), maize is one of the most important cereal crops - relatively sensitive to copper. An insufficient amount of copper in the diet can be dangerous for humans and animals as well. Copper is a component of antioxidant enzymes and its deficiency can disturb functioning of the antioxidant system in human or animal body (Hänsch and Mendel, 2009). Multi-purpose utilization of maize grain draws attention to the concentration of copper and manganese in kernels. Under Poland's conditions appropriate acquisition of copper and manganese in crop plants is of key importance, since in most cases, natural micronutrient availability in soils is generally low. Recent studies carried out by the National Chemical-Agricultural Centre showed low contents of available Cu in 34% of the soils analyzed. Content of avilable manganese in the soils examined was classified as medium (Lipiński, 2013). On the other hand, in Poland's agricultural practice, there have been observed no symptoms of extreme deficiencies of copper and manganese in maize because of low nutritional requirements for Cu and Mn in this crop (from 0.5 to 1.0 kg $\cdot ha^{-1}$). Nevertheless, insufficient acquisition of these micronutrients can lead to yield deterioration and loss. Demand for fertilization with an array of micronutrients grows especially in the farmsteads oriented toward intensive plant production. Yet, little attention has been so far paid to micronutrient performance, when applied using various fertilization modes. Furthermore, the influence of soil fertility on micronutrient uptake and relocation from plant tissues to grain has not been well documented. Time and again, micronutrient deficiencies become yield limiting factors, especially under the conditions impeding micronutrient availability, e.g. light soils, inadequate soil pH (Marschner, 1995). Besides, temperature and moisture are important factors affecting micronutrient availability to plants. Additionally, not enough manure fertilization, low tillage soil cultivation, crop rotation as well high nutritional requirements of succeeding crops are the reasons behind unsatisfactory availability of micronutrients in soils (Wei et al., 2006; Fageria et al., 2002). Contemporary high-yield maize varieties tend to contain lower concentrations of micronutrients in grain, when compared to lower-yield conventional cultivars (Feil et al., 2005). Under the conditions of a long-term field experiment, different fertilization treatments may alter soil nutrients and their available concentrations, which in turn may affect soil micronutrient levels (Li et al., 2007). The influence of phosphorus on micronutrients is related to the water content in the soil. Under field conditions, application of P considerably decreases water-soluble and extractable micronutrients (Bierman and Rosen, 1994).

In view of all the above mentioned aspects, the present study was conducted with the aim to: (1) assess copper and manganese nutritional status in maize at flowering stage, and (2) to examine changes of micronutrient contents and acquisition in the organs of maize under different fertilization treatments.

2. Materials and methods

2.1. Material

A stationary field experiment was conducted within a private farm at Wieszczyczyn (52º02' N 17º05'E), during 5 consecutive growing seasons (2007-2011). The trial was a component of a long-term study, established in the year 2000, in the randomized complete block design with four replications, set up on lessive soils developed from shallow light clayey sands on glacial tills (soil quality class IIIb in the Soil Classification System of Poland).

The field trials (a single-factor design) comprised 8 treatments:

- Control - no fertilization applied;
- WPN - no phosphorus fertilization; optimal fertilization with other nutrients (nitrogen, potassium and magnesium);
- WKN - no potassium fertilization; optimal fertilization with other nutrients (nitrogen, phosphorus and magnesium);
- W25 - 25% of recommended PK dose used in optimal fertilization, optimal fertilization with N and Mg;
- WP50 - 50% of recommended P dose used in optimal fertilization, optimal fertilization with other nutrients;
- WK50 - 50% of the recommended K dose used in optimal fertilization, optimal fertilization with other nutrients;
- W100 - 100% of recommended P and K doses, optimally balanced with reference to nitrogen;
- W100 PAPR - basic set of nutrients, P applied as partially acidulated phosphoric rock.

Winter wheat was cultivated as the forecrop of the studied maize variety *Veritis* (FAO: 230-240). The rates of phosphorus and potassium fertilization were calculated every year of observation, based on the expected yield of maize grain and existing soil P and K fertility. In W100 treatment (optimally balanced with reference to nitrogen), phosphorus was applied at a rate 26 kg $P \cdot ha^{-1}$/year (except for 2007: 35 kg $P \cdot ha^{-1}$), and potassium rates ranged from 100 kg $K \cdot ha^{-1}$ to 133 kg $K \cdot ha^{-1}$. Phosphorus was applied as single superphosphate (SSP), potassium - as potassium chloride (60% K_2O) and magnesium - as kieserite (27% MgO). All the basic fertilizers (PKMg) were applied in autumn. In W100 PAPR treatment, phosphorus was applied in the form of partially acidulated phosphate rock (PAPR), as an alternative phosphorus source (in place of SSP).

The assessments of maize copper and manganese contents regarded different plant organs and were carried out at 2 maize growth stages: BBCH 65 (flowering – in the ear leaf) and BBCH 89 (fully ripe - in: leaves, stems, ears, cob cores, husks and grain). The calculations were performed based on dry matter (D.M.).

The concentrations of Cu and Mn were assessed with the use of atomic absorption spectroscopy (SpectraAA-250 Plus Varian).

Copper and manganese accumulation values were determined based on the concentration of a given element and D.M. of maize organs. Data on maize yields obtained is provided in the paper by Bąk and Gaj (2016).

Copper Harvest Index (CuHI) and Manganese Harvest Index (MnHI) were calculated in accordance with the algorithm defining the relationship between accumulation of a given nutrient (Cu or Mn) in maize kernels (grain) and the total nutrient accumulation in maize at the stage of physiological maturity (fully ripe).

2.2. Statistical analysis

The effect of the experimental factor on nutrient accumulation and concentration under differentiated mineral fertilization with P and K was tested with 2-way ANOVA (mixed-effects model). A detailed description of the model used is presented by Bąk and Gaj (2016) and Bąk et al. (2016).

Data on the concentration of the nutrients (Cu and Mn) tested in maize organs were compared based on the graphical representation in heat maps, where 2D variables (defining micronutrient concentrations in maize organs depending on the treatments) were represented as colors. Cluster analysis allowed for treatment grouping with reference to the concentration of a given nutrient in maize organs in such a way as to demonstrate the strongest relationships within a given group and the weakest – among the groups. The dendrograms were prepared using Ward's hierachical clustering and the Euclidean distance. Causal relationships between the concentration, uptake, unit uptake of the nutrients tested and maize grain yield were tested using correlation coefficient.

3. Results and discussion

3.1. Concentration of Mn and Cu in the ear leaf

The results of the assessment of copper and manganese concentrations in the ear leaf of maize at the stage of flowering, showed that under mineral fertilization, nutrient concentration increased when compared to the control (Table 1). Zhang et al. (2004) point out that suitable NPK fertilization can enhance availability of copper and manganese in the soil, and hence – increase the concentration of these nutrients in the plant. In maize at the stage of flowering examined in the present study, the experimental factor differentiated copper concentration more than that of manganese. In the case of copper, significant differences ($p = 0.05$) were observed both between the treatments tested and with reference to the control. In flowering maize, leaf Cu concentration values were below the normative values 5 $mg \cdot kg^{-1}$-20 $mg \cdot kg^{-1}$, (Schulte and Kelling, 2000) and fluctuated in a narrow range from 3.34 $mg \cdot kg^{-1}$ to 4.14 $mg \cdot kg^{-1}$. The results obtained indicate copper deficiency in the leaves of flowering maize. At the same time, the lack of potassium fertilization had a stronger effect on the drop of Cu contents in the ear leaf when compared to the treatment with no phosphorus fertilization. Li et al. (2007) demonstrated that the concentrations of micronutrients in soil or in crops were strongly affected by available soil P and K concentrations.

On the part of manganese, no statistical differences were found between fertilizer treatments. Regardless of the treatment tested, Mn concentration in the ear leaf was at the normative level when compared to the threshold values determined by Schulte and Kelling (2000), i.e.: 19 $mg \cdot kg^{-1}$ -75 $mg \cdot kg^{-1}$ D.M. In the majority of the world's crop plants, Mn requirements are fulfilled at tissue levels, i.e.: 20 $mg \cdot kg^{-}$- 40 $mg \cdot kg^{-1}$ D.M (Jiang, 2006). Literature data (Mahler et al., 1992; Chalmers et al., 1999) indicated prevalent Mn deficiency in crop plants all over the world, and as a result yield production has been limited.

Table 1. Copper and manganese concentrations in the ear leaf of maize at flowering stage (BBCH 65), $mg \cdot kg^{-1}$ D.M.

	Control	WPN	WKN	W25	WP50	WK50	W100	W100 P as PAPR
Cu	3.35 c	4.05 ab	3.99 ab	3.72 abc	4.15 a	3.48 bc	3.61 abc	3.90 abc
Mn	19.08 b	26.70 a	28.47 a	27.84 a	31.12 a	28.91 a	30.36 a	28.10 a

*Means with the same letter are not significantly different; $\alpha = 0.05$ (Tukey's test)

Yet, Mn shortage is difficult to manage as this nutrient applied to the soil is very susceptible to rapid oxidation (Mortveld, 1994). In the present study, the chemical form of phosphorus in the fertilizer applied had no significant effect on Cu and Mn leaf concentration in maize at flowering. Correlation analysis with regard to relationships between grain yield and Mn or Cu nutritional status in maize at BBCH 65 stage showed a significant correlation for both nutrients tested. The stronger correlation was observed for manganese (r = 0.614) when compared with Cu (r = 0.420). At this growth stage, in comparison to the control, there were observed differentiated relationships: grain yield-Mn nutritional status and grain yield-Cu nutritional status, depending on the treatment. The relationships found indicate that under the conditions of intensive production, there exists a possibility to obtain grain yields considerably higher than the national average, as long as crop plants are suitably supplied with not only macronutrients, but also – micronutrients such as copper and manganese. More information on maize yields obtained is presented in the paper by Bąk and Gaj (2016).

3.2. Distribution of nutrients within organs of fully ripe maize

Micronutrients differ considerably with respect to distribution within plants and remobilization from plant organs (or tissues) to developing seeds (Grusak et al. 1999). In the present study, Cu contents in maize at physiological maturity (BBCH 89) varied depending on the plant organ analyzed and the treatment applied. The highest Cu concentration was observed in the leaves (Figure 1). In other maize organs examined, Cu concentration was decreasing in the following order: grain>cob cores>stems>husks. When compared to the control, mineral fertilization increased Cu concentration only in maize leaves. In the opinion of Quzounidou et al. (1996), distribution of copper in plant tissues depends on the form in which it is present in the plant, plant species, as well as plant population involved in uptake. No explicit effect of the experimental factor was observed with respect to copper concentration in maize grain. The highest Cu concentration ($2.7 mg\cdot kg^{-1}$) was observed in grain harvested from the treatment fertilized with P and K rates reduced to 25% (W25) of the optimal dose applied in W100% treatment. Grain Cu concentration observed in W25 significantly differed from the following treatments: W100, WK50,WKN, WP50 and W100 PAPR.

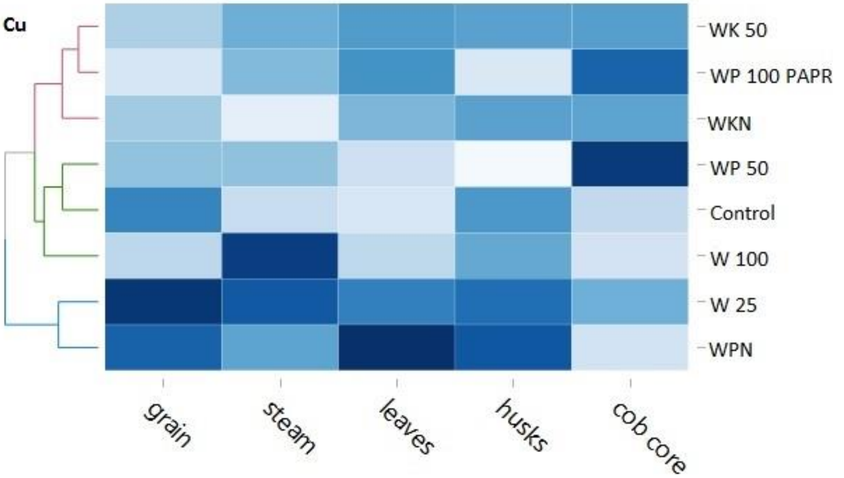


Figure 1. Effect of phosphorus and potassium fertilization on copper concentrations in maize parts, mg·kg^{-1} D.M. (BBCH 89 - fully ripe)

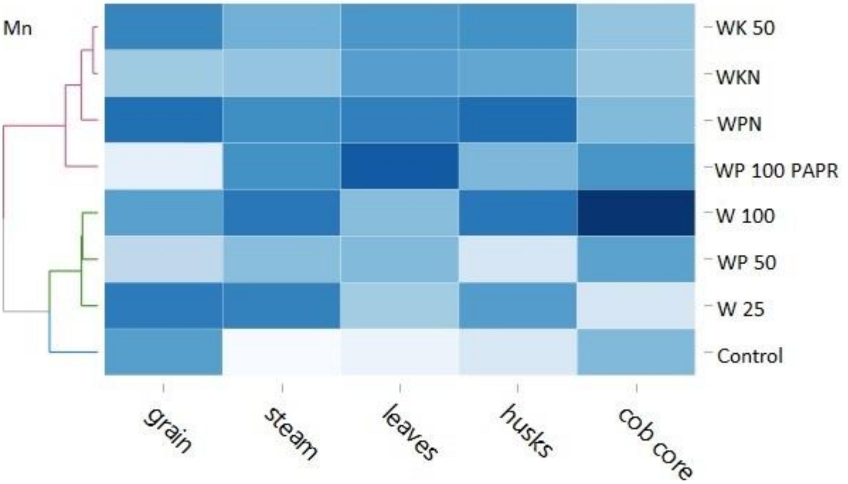


Figure 2. Effect of phosphorus and potassium fertilization on manganese concentrations in maize organs, mg·kg^{-1} D.M. (BBCH 89 - fully ripe)

When compared to the control, significantly lower grain Cu concentration was observed in WKN treatment (no K fertilization), whereas the absence of P fertilization (WPN treatment) caused an increase of Cu and Mn in maize grain. The study by Li et al. (2007) showed an increase of Cu concentration in maize and wheat grain as well as stems under the conditions of no fertilization with P and K, respectively. Li et al. (2010) suggest that excessive availability of phosphorus or potassium in the soil decreases copper availability due to the formation of precipitates $Cu_3(PO_4)_2$ or antagonistic activity of potassium against copper, which results in Cu reduction in wheat grains. Cluster analysis performed with respect to the treatments tested and Cu contents in maize organs distinguished 3 treatment groups (3 clusters same with regard to Cu concentration): (1) control, W100, WP50; (2) WK50,WKN, W100 PAPR; (3) W25, WPN.

In fully ripe maize (BBCH 89), Mn concentration was significantly differentiated due to the effects of the experimental factor (Figure 2). Mineral fertilization caused an increase of Mn concentration in all the maize organs analyzed, except for cob cores. As in the case of copper, the highest concentration of Mn was observed in maize leaves, and the lowest – in the stem. Leaf Mn concentration ranged from 32 $mg \cdot kg^{-1}$ D.M to 55 $mg \cdot kg^{-1}$ D.M, whereas Mn concentration in maize stems was 10-fold lower. In other organs analyzed, Mn concentration decreased in the following order: husks>cob core>grain. The increase of manganese concentration in grain under P fertilization was also observed by Xia et al. (2013). Graphic illustration of Mn concentration in the examined organs of fully ripe maize depending on the experimental factor effects is presented in Figure 2. Regardless of the organ examined, the strongest relationship between the treatments with respect to analogous Mn concentrations in maize was observed in 2 treatment groups (Control, WP50, W100, W25) and (WKN, WK50, WPN, W100 PAPR).

3.3. Copper and manganese uptake

Total uptakes of both manganese and copper were significantly differentiated due to the effect of the experimental factor. When compared to the control treatment, mineral fertilization significantly increased accumulation of the micronutrients studied (Figure 3-4).

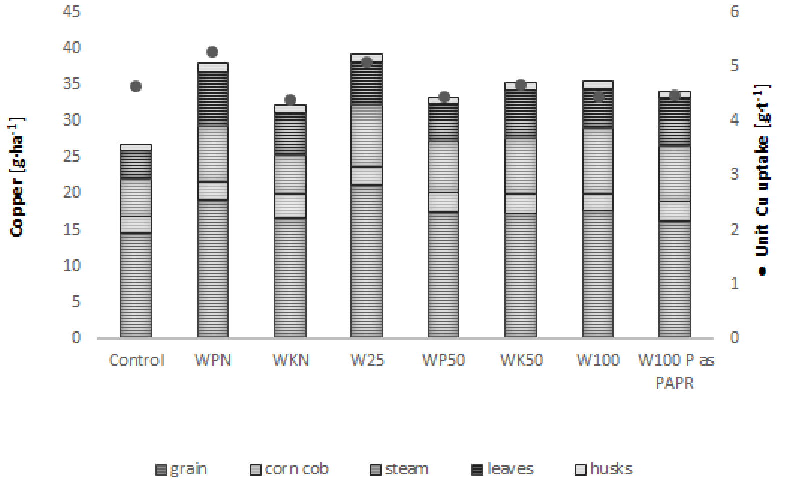


Figure 3. Effect of phosphorus and potassium fertilization on copper accumulation in maize organs and Cu unit uptake (BBCH 89 - fully ripe)

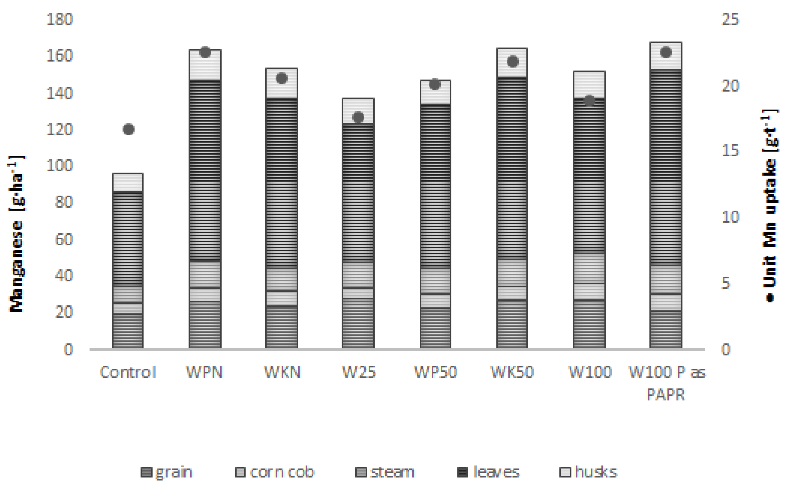


Figure 4. Effect of phosphorus and potassium fertilization on manganese accumulation in maize organs and Mn unit uptake (BBCH 89 - fully ripe)

However, P and K fertilization differentiated the total Cu and Mn accumulation in an ambiguous way. With respect to copper, the uppermost increase of its uptake in comparison to the control was observed in W25 treatment and amounted to 31.8%. The lowest - 23% increase of copper uptake was observed in WKN treatment. Ten-year long lack of K fertilization (WKN) reduced the total uptake both of Cu and Mn to a considerably bigger extent when compared to the lack of P fertilization (WPN). In the case of Cu, the difference (5.8 $g \cdot ha^{-1}$, i.e. 15%) between these treatments was statistically significant. WKN and WPN treatments showed no significant differences with reference to Mn uptake (9.6 $g \cdot ha^{-1}$, i.e. 5.9%). The study by Gaj et al. (2013) on triticale showed dissimilar relationships, as micronutrient accumulation in fully ripe triticale was shaped to much bigger extent by no fertilization with phosphorus or potassium. Pearson's correlation - measuring strength of association between maize grain yield and the total Cu and Mn uptake - showed significant relationships which depended on the micronutrients and treatments tested (Table 2). Statistically significant relationships between grain yield and the total accumulation of both Cu and Mn were observed in the following treatments: WPN, WP50 and W100 as PAPR. In W100 treatment, the significant relationship was observed only with respect to Cu, and in WKN, W25 and WK50 treatments – only with respect to Mn.

3.4. Maize grain harvest indexes

Nutrient harvest index is defined as a quotient of nutrient uptake in grain and nutrient partitioning in the crop plant. The value obtained gives indication of how efficiently the plant utilized acquired nutrients for grain production (Fageria and Baligar, 2005). Evaluation of grain harvest indexes obtained for Cu and Mn clearly indicated that regardless of the treatment tested, the majority of copper was accumulated in maize grain, whereas manganese – in the leaves (Table 3, Figures 3-4).

When compared to the control treatment, a decreasing trend was observed in copper accumulation in grain as a result of mineral fertilization. The lowest

Table 2. Pearson's correlation coefficients between maize grain yield and the total and partial Cu and Mn acquisition by maize organs

Parameters	Control	WPN	WKN	W25	WP50	WK50	W100	W100 P as PAPR
Cu total uptake	0.367	0.614*	0.182	0.401	0.487*	0.346	0.470*	0.727*
Mn total uptake	0.427	0.715*	0.628*	0.458*	0.461*	0.790*	0.230	0.529*
Cu grain uptake	0.513*	0.694*	0.140	0.589*	0.640*	0.318	0.606*	0.833*
Mn grain uptake	0.451*	0.745*	0.562*	0.682*	0.651*	0.409	0.409	0.707*
Cu steam uptake	0.055	0.350	0.142	0.101	0.076	-0.124	0.139	0.603*
Mn steam uptake	-0.061	-0.474*	-0.280	-0.523*	-0.365	0.151	-0.012	-0.362
Cu leaves uptake	0.007	0.104	0.040	0.045	-0.105	0.116	0.224	0.129
Mn leaves uptake	0.438	0.697*	0.489*	0.395	0.337	0.686*	0.145	0.561*
Cu husks uptake	0.364	0.187	0.189	0.150	0.137	0.301	0.547*	0.510*
Mn husks uptake	-0.221	-0.052	0.460*	-0.031	0.485*	0.423	-0.015	-0.008
Cu cob core uptake	-0.041	0.002	0.079	0.308	0.270	0.677*	0.020	-0.160
Mn cob core uptake	0.127	-0.008	0.054	0.303	0.304	0.473*	0.312	-0.168

*p<0.05

CuHI value was obtained in W100 PAPR treatment. A significant correlation between maize grain yield and Cu accumulation was found in most of the treatment studies, except for WKN and WK50 (Table 3).

Manganese acquisition in grain expressed as harvest index MnHI ranged from 13.7 (W100 PAPR) to 20.9 (control). MnHI values obtained in the present study were analogous to those reported by other authors (Xia et al., 2013, Li et al., 2007). In the present study, a considerable portion of manganese (50 - 64% of the total uptake) was accumulated in maize leaves, which indicates low mobility of this nutrient within the plant (Figure 4). In other words, the results clearly

Table 3. Copper and manganese accumulation index depending on phosphorus and potassium fertilization

Treatments	CuIH	MnIH
Control	53.95 a	20.86 a
WPN	49.12 ab	16.05 cd
WKN	51.28 ab	15.47 cd
W25	53.30 ab	19.81 ab
WP50	51.63 ab	15.45 cd
WK50	48.65 b	16.28cd
W100	49.16 ab	17.78 cd
W100 P as PAPR	48.07 b	13.69 d

*Means with the same letter are not significantly different; α = 0.05 (Tukey's test)

demonstrated that Mn cannot be mobilized from the leaves of maize, even though Mn is lacking in grain. The above relationship was also confirmed by Person and Rengel (1994, 1995) in the study on wheat. The question still remains whether Mn immobility in the leaves of some plant species is attributable to no exchangeable incorporation of this nutrient into high-molecular-weight compounds or structures within the cell or to the requirement for chelates in phloem loading. In the present study, significant relationships between grain yield and manganese accumulation in the leaves of fully ripe maize were found in 4 of 8 tested treatments (Table 3).

The unit uptakes of copper and manganese were differentiated by the experimental factor (Figures 3-4). When compared to the control, in all the fertilizer treatments tested, Mn unit uptake was increased and ranged from 16.7 $g \cdot t^{-1}$ to 22.7 $g \cdot t^{-1}$. At the same time, copper unit uptake ranged from 4.4 $g \cdot t^{-1}$ to 5.3 $g \cdot t^{-1}$. Of all the treatments applied, only W25 and WPN showed a significant increase of Cu unit uptake in comparison to the control. Higher values of the unit uptake of both copper and manganese were obtained in the treatment with neglected phosphorus fertilization (WPN). The form of phosphorus applied as the fertilizer significantly differentiated only manganese unit uptake – higher values of this parameter were obtained in the treatment with partially acidulated phosphate rock.

4. Conclusions

- The assessment of the nutritional status carried out in the ear leaf of maize at flowering (BBCH 65), showed that regardless of the treatment tested, copper concentration was below the normative values and that of manganese was in the range of the optimal values.
- The significant correlation was found between maize grain yield and copper and manganese concentrations observed in the ear leaf of maize at BBCH 65.
- In fully ripe maize (BBCH 89), of all the plant organs examined, the highest contents of copper and manganese were observed in the leaves, and the lowest - in the stems.
- Mineral fertilization significantly increased the total uptake of Cu and Mn. Regardless of the effect of the experimental factor, Cu was mainly accumulated in maize grain (50% of the total accumulation) and manganese in the leaves (50-64%).
- Ten-year-long absence of fertilization with potassium reduced the total uptake of copper and manganese to a considerably bigger extent when compared to no phosphorus fertilization within the same period of time.

REFERENCES

Bąk K., Gaj R. (2016): The effect of differentiated phosphorus and potassium fertilization on maize grain yield and plant nutritional status at the critical growth stage. J. Elem. 21(2): 337-348.

Bąk K, Gaj R., Budka A. (2016): Accumulation of nitrogen, phosphorus and potassium in mature maize under variable rates of mineral fertilization. Fragm. Agron. 33(1): 7-19.

Bierman P.M., Rosen C.J. (1994): Phosphate and trace metal availability from sewage-sludge incinerator ash. J. Environ. Qual. 23: 822-830.

Chalmers A.G., Sinclair A.H., Carver M. (1999): Nutrients other than nitrogen, phosphorus and potassium (NPK) for cereals. HGCA Res. Rev. 41 London.

Fageria N.K, Baligar V.V., Clark R.B. (2002): Micronutrients in crop production. Adv. Agron. 77: 185-268.

Fageria N.K, Baligar V.V. (2005): Enhancing nitrogen use efficiency in crop plants. Adv. Agron. 88: 97-185.

Fageria N.K., Baligar V.C., Li Y.C. (2008): The role of nutrient efficient plants in improving crop yields in the twenty first century. J. Plant Nutr. 31(6): 1121-1157. DOI:1080/01904160802116068.

Feil B., Moser S.B., Jampatong S. (2005): Mineral composition of the grains of tropical maize varieties as affected by pre-anthesis drought and rate of nitrogen fertilization. Crop Sci. 45: 516-523.

Gaj R**.,** Przybył J., Górski D., Rębarz K. (2013): The effect of different phosphorus and potassium fertilization on the content and uptake of microelements (Zn, Cu, Mn) by winter triticale. II Uptake of nutrients. Zesz. Nauk Roln. Wrocław Seria Rolnictwo 104: 19-26

Grusak M., Pearson J.N., Martentes E. (1999): The physiology of micronutrient homeostasis in field crops. Field Crops Res. 60: 41-56.

Hänsch R., Mendel R.R. (2009): Physiological functions of mineral micronutrients (Cu, Zn, Mn, Fe, Ni, Mo, B, Cl). Current Option in Plant Biology 12: 259-266.

Jiang W.Z. (2006): Mn use efficiency in different wheat cultivars. Environ. Experimental Botany 57: 41-50.

Li B.Y., Zhou D.M., Cang L., Zhang H.L., Fan X.H., Qin S.W. (2007): Soil micronutrient availability to crops as affected by long-term inorganic and organic fertilizer applications. Soil & Tillage Res. 96: 166-173.

Li B.Y., Huang S.M., Wei M.B, Zhang H.L., Shen A.L., Xu J.M.m, Ruan X.L. (2010): Dynamics of soil and grain micronutrients as affected by long-term fertilization in an aquic incptisol. Pedosphere 20(6): 725-735.

Lipiński W. (2013): Zasobność gleb Polski w mikroelementy. Studia i Raporty IUNG-PIB 34(8): 121-131.

Mahler R.L., Li G.C., Wattenbarger D.W. (1992): Manganese relationshps in spring wheat and spring barley production in Northern Idaho. Commun. Soil Sci. Plant Anal. 23: 1671-1692.

Marschner, H. (1995): Mineral nutrition in higher plants. Academic Press, London.

Mortvedt J.J. (1994): Needs for controlled availability micronutrient fertilizers. Fertil. Res. 38: 213-221.

Person J.N., Rengle Z. (1994): Distribution, remobilization of Zn and Mn during grain development in wheat. J. Exp. Bot. 45: 1829-1835.

Person J.N., Rengle Z. (1995): Uptake and distribution of ^{65}Zn and ^{54}Mn in wheat grown at sufficient and deficient levels of Zn and Mn. I. During vegetative growth. J. Exp. Bot. 46: 833-839.

Schulte E., Kelling K. (2000): Plant Analysis: a diagnostic tool. University of Wisconsin-Madison. Available online at: www.ces.pardue.edu/extmedia/NCH/NCH-46.html

Quzounidou G., Ciamporova M., Moustakas M., Karataglis S. 1995. Responses of maize (*Zea mays* L.) plants to copper stress, growth, mineral content and ultrastructure of roots. Environ. Exp. Bot. V. 35(2): 163-176.

Van Campen D.R., Glahn R.P. (1999): Micronutrient bioavailability techniques: accuracy, problems and limitations. Field Crops Res. 60: 93-113.

Wei X.R., Hao M.D., Shao M.G., Gale W. (2006): Changes in soil properties and availability of soil micronutrients after 18 years of cropping and fertilization. Soil Till. Res. 91: 120-130.

Xia HY., Zhao JH., Sun JH., Xue YF., Eagling T., Bao XG., Zhang FS., Li L. (2013): Maize grain concentrations and above-ground shoot acquisition of micronutrients as affected by intercropping with turnip, faba bean, chickpea, and soybean. Sci China Life Sci. 56: 823-834, DOI: 10.10007/s11427-013-4524-y.

Zhang R., Guo Y.X., Nan C.Q. (2004): Study of trace elements of wheat grain in different fertili treatments. Acta Bot. Boreal. Occident. Sin. 24: 125-129.

A4

Journal of Elementology ISSN 1644-2296

Bąk K., Gaj R., Budka A. 2016. *Distribution of zinc in maize fertilized with different doses of phosphorus and potassium*. J. Elem., 21(4): 989-999. DOI: 10.5601/jelem.2015.20.3.1095

ORIGINAL PAPERS

DISTRIBUTION OF ZINC IN MAIZE FERTILIZED WITH DIFFERENT DOSES OF PHOSPHORUS AND POTASSIUM

Krzysztof Bąk[1], Renata Gaj[2], Anna Budka[3]

[1]Poldanor SA, 77-320 Przechlewo
[2]Department of Agricultural Chemistry and Environmental Biogeochemistry
[3]Department of Mathematical and Statistical Methods
Poznan University of Life Sciences

Abstract

Evaluation of the nutritional status of zinc and other micronutrients in maize at the critical growth stages is an important diagnostic and prognostic factor that plays a substantial role in shaping its final yield. A hypothesis was verified that the application of different phosphorus and potassium fertilization doses affected the nutritional status of zinc in maize at the critical growth stages: leaf development (BBCH 17) and flowering (BBCH 65), as well as the zinc accumulation at the stage of ripening (BBCH 89, fully ripe). A single factor field study was conducted for 5 consecutive plant growing seasons (2007-2011). The results showed that mineral fertilization significantly increased zinc concentration in maize leaves at BBCH 17 and BBCH 65 growth stages. Regardless of the effects of the experimental factor, the Zn leaf content in maize at both critical growth stages was much below the standard value. Although the zinc concentration observed at the leaf development stage was low, no significant relationship was found between the zinc nutritional status in maize at that time and the subsequent grain yield. Stronger relationships between the zinc nutritional status in maize and grain yield were observed at the flowering stage. The total accumulation of zinc in maize was significantly differentiated by the experimental factor. The chemical form of phosphorus applied had no significant effect on Zn content in maize at the critical growth stages as well as on the accumulation of this nutrient in fully ripe plants. The ZnHI value obtained in the control treatment was 51.7%, whereas the values achieved in fertilizer treatments were higher and ranged from 52.9% (W100 PAPR – with partially acidulated phosphate rock) to 57.3% (W25 – 25% of K and P recommended rate). Correlation analysis on maize yield and zinc accumulation showed that yield volumes were determined most strongly by zinc accumulation in maize vegetative organs (especially husk leaves).

Keywords: critical growth stages, Zn accumulation, Zinc Harvest Index.

dr hab. Renata Gaj, Department of Agricultural Chemistry and Environmental Biogeochemistry, Poznań University of Life Sciences, Wojska Polskiego str. 71F, 60-625 Poznań, Poland, email:grenata@up.poznan.pl

INTRODUCTION

Zinc is an essential micronutrient in human and animal diets. Raising the zinc concentration in crop plants has recently become one of the most important goals in view of the high consumption of zinc deficient cereal products (Cakmak et al. 1996, 2010). Deficiency of zinc has been observed in patients, especially in children, affected by several illnesses (Stain 2009, Cakmak 2008). According to the World Health Organization (WHO 2002), more than 2 billion people, mainly in Africa and Asia, suffer from zinc shortages in their everyday diet. Latest studies (Zhang et al. 2013, Hossain et al. 2008) have shown that the Zn content in maize grain can be enhanced either by soil application of Zn or by seed priming with this element. In most cases, the cause of zinc deficiency in plants is not the soil insufficiency but poor availability of this element (Kalayci et al. 1999). Zinc availability depends on many factors, such as soil reaction, density and moisture as well as organic matter content (Chang et al. 2007, Sadeghzadeh 2013). The zinc content in plants is differentiated and depends on plant species, variety and physiological characteristics (Cakmak et al. 1998, Oury et al. 2006). The accumulation of zinc in sensitive plants, such as maize, stimulates the uptake of nitrogen and its physiological activity (Potarzycki, Grzebisz 2009). On the other hand, plant nitrogen management is strongly associated with the carbohydrate management. Relationships among processes in plants induce such responses as an enhanced uptake of water and mineral nutrients, including zinc. Wrońska et al. (2007) showed that good nutrition of maize with zinc could increase nitrogen fertilization efficiency and consequently lower fertilization costs and nitrogen losses. In the last decades, Zn deficit in the soil-crop system has spread due to high yielding of selected maize varieties, increased purity of chemical fertilizers and progressively more intensive cropping systems (Fageria et al. 2002).

Among numerous factors affecting the zinc activity in plants, phosphorus plays a specific role (Mousavi 2011). The action of this nutrient has to be considered from two viewpoints, i.e. its influence on the soil and on the plant. Generally, with an increased phosphorus content in the soil or enlarged supply of P in fertilizers, the plants' uptake of zinc decreases more or less drastically, and often beyond a level which can be attributed to dilution effects caused by the plants' higher growth. Under natural conditions, considerable differentiation in the zinc content observed in soil is driven by natural, e.g. the parent rock, soil dust fallout, and anthropogenic factors, e.g. mineral fertilization, agricultural intensity (Amrani et al. 1999, Kaniuczak et al. 2009*a*,*b*). The amount of active Zn^{2+} in soil is controlled by phosphorus. Excessive phosphorus causes Zn regress towards inactive orthophosphoric precipitate and blocks zinc cation uptake by plants through the uptake of calcium cations along with orthophosphoric anions. The antagonistic action of phosphorus in the plant is a result of the binding of zinc by inorganic orthophosphates in the root apoplast and cell cytoplasm (Cakmak, Marschner 1987). Some symptoms seen as Zn deficiency in fact indicate an excess of inorganic phosphorus. Nevertheless, interactions between P uptake effciency and Zn uptake are largely unknown.

In the present study, it was assumed that different phosphorus and potassium fertilization doses influenced the Zn concentration and accumulation in maize. This hypothesis was verified in a single factor experiment with different doses of P and K fertilization at constant amounts of nitrogen and magnesium. The aim of the study was to evaluate the influence of different P and K fertilization doses on: (1) Zn concentration in maize at the critical growth stages, (2) accumulation and redistribution of zinc in plant parts at harvest and (3) Zn effect on grain yield.

MATERIAL AND METHODS

The study was carried out for 5 consecutive plant growing seasons (2007-2011). A closed field experiment on maize (variety *Veritis*) was established on a farm in the region Wielkopolska (52°02′ N 17°05′ E). The trial (single factor experiment) was part of a longitudinal study carried out since 2000, and established in a randomized complete block design with four replications for each treatment. Methodological details are described by Bąk, Gaj (2016). The experimental factor comprised different mineral fertilization doses of phosphorus and potassium. The recommended balanced fertilization for W100 treatment was designed based on the soil nutrient availability, the uptake rate of a specific nutrient and the expected yield. At constant N and Mg fertilization, further P and K doses were reduced to 25% and 50% of W100 treatment (W25 – 25% of K and P recommended dose as compared to optimally fertilized treatment; WP50 – 50% of P recommended dose; WK50 – 50% of K recommended dose).

Additionally, the control treatments with no potassium or phosphorus added (WKN and WPN, respectively) as well as the absolute control (no mineral fertilization) were tested. In W100 PAPR treatment, partially acidulated phosphate rock (PAPR) was applied as an alternate source of phosphorus applied as single superphosphate. Phosphate rock used in the study contained 10.2% of P and its acidification was 50% (i.e. sulfuric acid used up during a technological process run to obtain the product equalled 50% of the amount necessary for production of single superphosphate). During the trial, winter wheat was grown as a preceding crop. The experiment was set up on lessive soils on glacial tills (soil quality class IIIb in the Polish soil valuation system) with medium P and K availability. Phosphorus and potassium were applied in the autumn, at the doses corresponding to the experimental design. Assessments of the maize zinc content were carried out at the following maize growth stages: BBCH 17 (leaf development), BBCH 65 (flowering) and

BBCH 89 (ripening - fully ripe). At BBCH 17, the zinc content was assessed in leaves randomly collected from 10 maize plants growing on every experimental plot, at BBCH 65 – in the leaf below maize ear (earleaf), and at BBCH 89 – in the following maize parts: leaves, stems, ears, corn cobs (central core of an ear), husks and kernels (grain).

The value of zinc uptake was derived from the multiplication of the values obtained for: maize grain yield – data available in the paper by Bąk and Gaj (2016) x maize organ dry weight – data available from the authors of the present paper x Zn concentration in the maize parts examined. Zn Harvest Index was calculated based on the algorithm expressing the ratio of Zn accumulation in maize kernels (grain) and the total Zn accumulation in maize at the stage of physiological maturity.

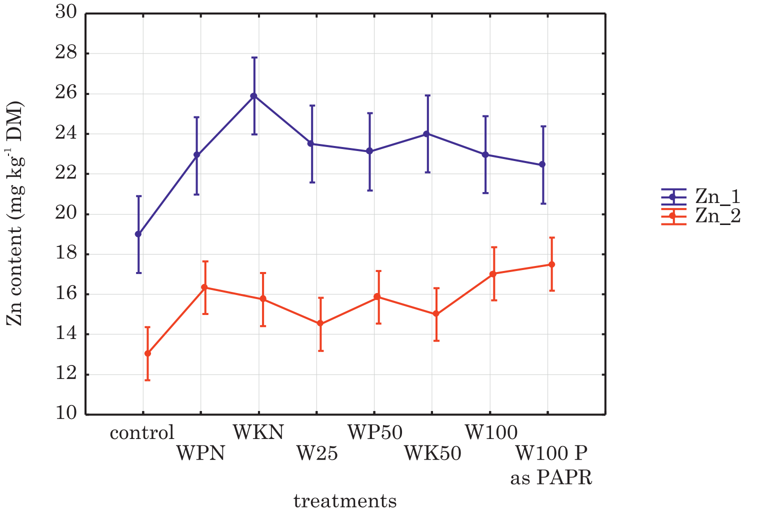
The plant material was dry mineralized at 550°C. The ash was mixed with 2 cm^3 of HNO_3 with distilled water (1:1) and then transferred to test tubes with distilled water added to 15 cm^3. The zinc concentration was assessed by atomic absorption spectroscopy (SpectraAA-250Plus Varian).

Statistical tests were performed using ANOVA for single factor experiments. Mean values of variables (Zn concentration in plant organs examined at different growth stages) were tested separately by means of ANOVA F-test ($\alpha = 0.05$). In order to determine homogenous groups ($\alpha = 0.05$), mean values of Zn concentrations with reference to the treatments examined were tested using the Tukey's test (multiple comparison procedure). Principal Component Analysis (PCA) allowed us to show regularities among maize grain yield, Zn concentration in plant organs and Zn uptake (in each treatment separately).

RESULTS AND DISCUSSION

Zinc concentrations in maize parts

The experimental factor significantly differentiated Zn concentrations in maize at all the growth stages examined as well in the plant organs analyzed (Figure 1, Table 1). Different P and K fertilization doses increased the Zn concentration in maize leaves at the stage of 7 unfolded leaves (BBCH 17), when compared to the control (Figure 1). Significant statistical differences were found not only with respect to the control treatment, but also between the treatments examined. The highest Zn concentration was observed in W100 treatment (optimally balanced with reference to nitrogen). The chemical form of phosphorus applied had no effect on shaping differences in leaf contents of Zn between the treatments. Regardless of the mineral fertilization level, in the early stage of maize growth, the zinc concentration in leaves ranged from 19 mg kg^{-1} to 24 mg kg^{-1}, i.e. it was considerably below the threshold level (55 mg kg^{-1} – 99 mg kg^{-1}). According to Zhang et al. (1991), plants containing less than 20 mg kg^{-1} of zinc in their tissues suffer



Vertical bars indicato 0.95 confidence levels, Zn 1 – Zn concentration in leaves at BBCH 17, Zn 2 – Zn concentration in leaves at BBCH 65

Fig. 1. Zinc concentration in maize leaves at the critical growth stages depending on differentiated P and K fertilization

Table 1

Effect of phosphorus and potassium fertilization on zinc concentrations in maize parts, mg kg^{-1} DM (BBCH 89 - fully ripe)

Treatments	Grain	Leaves	Husk leaves	Stem	Cob core
Control	15.33*abc**	6.040*ab*	7.242*a*	15.06*bc*	28.04*a*
WPN	15.48*ab*	6.016*ab*	6.879*a*	16.08*abc*	18.06*bc*
WKN	13.61*cd*	5.026*b*	5.278*a*	14.46*bc*	17.11*c*
W25	15.62*a*	6.454*a*	5.860*a*	17.34*ab*	17.51*bc*
WP50	13.30*d*	5.521*ab*	5.076*a*	14.10*c*	18.09*bc*
WK50	14.90*abcd*	5.806*ab*	6.245*a*	16.41*abc*	18.54*bc*
W100	14.49*abcd*	5.380*ab*	5.995*a*	19.14*a*	18.64*bc*
W100 P as PAPR	13.74*bcd*	5.626*ab*	6.426*a*	14.51*bc*	22.89*ab*

* Means with the same letter are not significantly different; α = 0.05 (the Tukey's test).

from zinc deficit. A low concentration of zinc in a plant can be a result of an increased phosphorus uptake. On the other hand, high Zn contents decrease P uptake (Mousavi 2011). Kizilgoz and Sakin (2010) state that P/Zn ratios observed in the plant are useful in an assessment of the P and Zn status. In young leaves, P/Zn ratios ranging from 106 to 151 are considered as adequate for a plant's optimal growth, and those above 231 indicate Zn deficiency. In the present study, regardless of the treatment applied, P/Zn ratios ranged from 91.34 to 122.90. While there can be several chemical zinc compounds in the soil, plants are able to absorb only zinc ions. Other chemical compounds can affect the process of zinc uptake from the soil into the plant as well as zinc accumulation in plant tissues. Apart from various soil features that affect zinc uptake by plants, the chemical form of this nutrient occurring in the soil plays an important role in the process (SPIAK 1996). Although the zinc concentration in maize leaves observed in this study was low, no significant relationship was found between maize Zn nutritional status and the grain yield obtained. The correlation analysis on the zinc concentration in maize leaves at the early growth stage and the yield of maize grain showed a significant relationship only in W100 PAPR treatment (with partially acidulated phosphate rock as the alternate phosphorus source).

Different mineral fertilization regimes supplying phosphorus and potassium significantly differentiated Zn concentrations in maize plants at the flowering stage (BBCH 65) – Figure 1. The leaf Zn concentration increased as a result of fertilization, although it was lower than at BBCH17 stage. Significant differences were observed among fertilized treatments and when compared to the control. Reduction of a potassium dose to 50% of W100 dose (treatment WK 50) or elimination of this nutrient (treatment WKN) resulted in a greater decrease of the Zn leaf concentration than in the analogous treatment with phosphorus (WPN). Regardless of the treatment tested, the Zn concentration in the leaf below the ear (earleaf) was much lower than the norm (19-75 mg kg^{-1}) determined by SCHULTE and KELLING (2000). An evaluation of the nutritional status of zinc and other nutrients at the maize flowering stage is of great importance since this stage comprises one of the key growth phases of maize that have a significant influence on the final yield. At the flowering stage, zinc increases the vitality of pollen grains, and therefore it advances the development of more kernels (WESTAGE et al. 2003). In contrast to BBCH 17, a stronger relationship was observed between the final yield and zinc nutritional status at the maize flowering stage (BBCH 65). Significant correlations were found in the following treatments: WPN (0.769), WKN (0.616) and WK50 (0.666). Another factor that affected the Zn concentration in maize at the flowering stage was the unfavourable weather, especially before flowering in 2008 and 2009. The rainfalls in 2008 and 2009 were 65% and 16%, respectively, of the long-term precipitation data. Water deficiency resulted in lower values obtained for the Zn leaf concentration. This could have been caused by the limited root growth in the soil or else by a depressed activity of microorganism activity and decreased release of zinc from organic matter (ALAM et al. 2010). According to SUBEDI and MA (2005) as well as GRZEBISZ at al. (2008), an intensive uptake of the majority of mineral nutrients, including zinc, occurs in the period prior to flowering. Water stress inhibits the transfer of zinc (mainly through diffusion) from the soil toward the root surface (CAKMAK et al. 1996, HONG and JI-YUN 2007).

At BBCH 89 (fully ripe), the experimental factor significantly differentiated Zn concentrations in the maize organs examined (Table 1). The tested fertilization had no significant effect only in the case of husk leaves. The zinc concentrations decreased as follows: cob core > grain> stem > husk leaves > leaves. This order indirectly indicates zinc mobility in maize organs during the plant growing season. When compared to other plant parts, a higher zinc concentration in the vegetative parts of maize cobs reflects the temporary status of zinc, before reaching the final storage organ, i.e. grain. POTARZYCKI (2010) points out that the cob core can be considered as an important buffer storage organ in view of relatively low zinc amounts observed in grain and those accumulated in the cob core. The highest zinc content in maize kernels (15.48 mg kg^{-1}) was observed in the W 25 (Table 1), whereas two- and three -fold lower Zn concentrations were found in maize leaves and husks. KUTMAN et al. (2011) found that extreme Zn deficiency enhanced the content of phosphorus and its transport toward grains.

Zinc uptake

The total accumulation of zinc in maize was significantly differentiated by the experimental factor (Figure 2). Maize plants cultivated in plots with

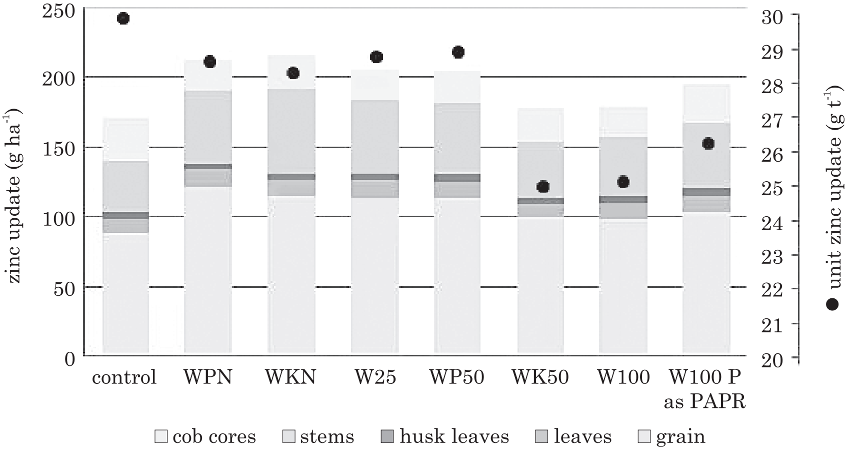


Fig. 2 Effect of phosphorus and potassium fertilization on zinc accumulation in maize parts (BBCH 89 – fully ripe)

no potassium fertilization for 10 years accumulated considerably less zinc when compared to the treatment with no phosphorus added for 10 years. This result confirms general findings on mutual relationships between P and Zn. Numerous studies have been conducted on zinc and phosphorus interactions, all confirming that the lack of balance between zinc and phosphorus in the plant due to excessive accumulation of phosphorus leads to the deficiency of zinc (DAS et al. 2005, SALIMPOUR et al. 2010). As indicated by literature, phosphorus is an essential element negatively affecting the zinc uptake by plants because the soil content of zinc declines at higher soil content of phosphorus. YANG et al. (2011) report that excess phosphorus in the soil environment acts antagonistically toward Zn, and therefore the Zn uptake by roots decreases. Furthermore, ZHAO et al. (1998) showed Zn deficiency in cereal grains under the conditions of increasing phosphorus fertilization. In the present study, zinc accumulation in the treatment with PAPR as a source of phosphorus was not significantly different from the W100 treatment. A decreasing trend was just observed due to the PAPR application.

An important component of the evaluation of nutrient accumulation in final yield of maize is an assessment of nutrient distribution in plant organs, with particular attention paid to the relative share of a given nutrient observed in harvested grain. Zinc Harvest Index (ZnHI) defines the relative share of grain-accumulated nutrients in the total plant accumulation. In the present study, among the maize organs analyzed, the highest Zn accumulation was observed in kernels, then in the stem and in the remaining vegetative plant parts examined (Figure 2). The ZnHI value obtained in the control treatment was 51.7%, whereas the values obtained in fertilized treatments were higher and ranged from 52.9% (W100 PAPR) to 57.3% (W25).

Differentiated fertilization with phosphorus and potassium had no significant effect on the rate of specific nutrient uptake (Figure 2). The value of the Zn uptake rate in fully ripe maize specifies the quantity of this nutrient in yield (here: grain). The effects of different doses of phosphorus and potassium on the rate of Zn uptake were reflected in a tendency of the values of this parameter being lower than in the control.

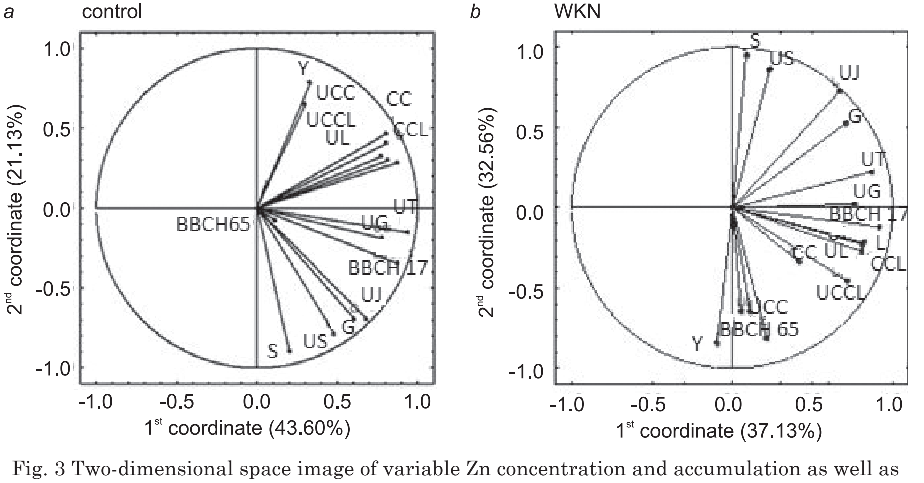


Fig. 3 Two-dimensional space image of variable Zn concentration and accumulation as well as maize grain yield: Y – yield, Zn 1 – Zn concentration in leaves at BBCH 17, Zn 2 – Zn concentration in leaves at BBCH 65, G – Zn concentration in grain at BBCH 89, L – Zn concentration in leaves at BBCH 89, CCL – Zn concentration in husks at BBCH 89, S – Zn concentration in steam at BBCH 89, CC – Zn concentration in corn cob at BBCH 89, UG – Zn accumulation in grain, UL – Zn accumulation in leaves, UCCL – Zn accumulation in husks at BBCH 89, US – Zn accumulation in stem at BBCH 89, UCC – Zn accumulation in corn cob at BBCH 89, UT – total Zn accumulation in corn cob at BBCH 89, UJ – unit Zn uptake

Relationships (correlations) between maize grain yield and the total Zn accumulation, as well as Zn uptake by the plant organs examined at BBCH 89 were tested using Principal Component Analysis (PCA). Regardless of the impact of the experimental factor, the analysis of correlation with regard to relations between maize grain yield and Zn accumulation in fully ripe plants showed that the yield mostly depended on the Zn accumulation in vegetative parts (especially husks) of maize. Significant relationships between maize yield and Zn accumulation in husk leaves were found in the majority of the treatments (e.g. the control, Figure 3*a*), except the WKN treatment, which showed a weak correlation (Figure 3*b*).

CONCLUSIONS

1. When compared to the control, differentiated mineral fertilization with phosphorus and potassium significantly increased the zinc content in organs of maize at all the growth stages analyzed.

2. Regardless of P and K fertilization doses, zinc concentrations in maize leaves at the critical growth stages (BBCH 17 and BBCH 65) were lower than the threshold values.

3. The assessment of zinc in maize leaves at the flowering stage (BBCH 65) was more useful for yield prognosis than an analogous assessment carried out on maize at growth stage BBCH 17.

4. Notwithstanding the effect of the experimental factor, maize grain yield was determined mostly by zinc accumulation in vegetative organs (especially in husk leaves).

5. The chemical form of phosphorus applied had no significant effect on the Zn content in maize at the critical growth stages or on the Zn accumulation in fully ripe plants.

REFERENCES

Alam M.N., Abedin M.J., Azad Mak 2010. *Effect of micronutrients on growth and yield of onion under calcareous soil environment*. Int. Res. J. Plant Sci., 1(3): 056-061.

Amarani M., Westfall D.G., Peterson G.A. 1999. *Influence of water solubility of granular zinc fertilizers on plant uptake and growth*. J. Plant Nutr., 22(2): 1815-1827.

Bąk K., Gaj R. 2016. *The effect of differentiated phosphorus and potassium fertilization on maize grain yield and plant nutritional status at the critical growth stage*. J. Elem., 21(2): 337-348. DOI: 10.5601/jelem.2015.20.3.996

Cakmak I. 2008. *Enrichment of cereal grains with zinc: Agronomic or genetic bifortification?* Plant Soil, 302: 165-172.

Cakmak I., Torun B., Ernoglu B., Ozturk L., Marschner H., Kalayci M., Ekiz H. 1998. *Morphological and physiological differences in cerals in response to zinc deficiency*. Ephytica, 100: 349-357.

Cakmak I., Marschner H. 1987. *Mechanism of phosphorus induced zinc deficiency in cotton*. III. *Changes in physiological availability of zinc in plants*. Physiol. Plant., 70: 13-20.

Cakmak I., Pfeiffer W.H., McClafferty B. 2010. *Biofortification of durum wheat with zinc and iron*. Cereal Chem., 87: 10-20.

Cakmak I., Yilmaz A., Kalayci M., Ekiz H., Torun B., Erenoglu B., Braun H.J. 1996. *Zinc deficiency as a critical problem in wheat production in Central Anatolia*. Plant Soil, 18: 165-172.

Chang W.Y., Lu B.Y., Yun J.J., Ping Y., Zheng X.S., Xin L.G., Wei S., Chun Z. 2007. *Sufficiency and deficiency indices of soil available zinc for rice in the alluvial soil of the coastal Yellow Sea*. Rice Sci., 14(3): 223-228.

Das K., Dang R., Shivananda T.N., Sur P. 2005. *Interaction between phosphorus and zinc on the biomass yield attributes of the medical plant stevia (Stevia rebaudiana)*. Sci. World J, 5: 390-395.

Fageria N.K, Baligar C, Clark R.B. 2002. *Micronutrients in crop production*. Adv. Agron., 77: 185-268.

Grzebisz W., Wrońska M., Diatta J.B., Szczepaniak W. 2008. *Effect of zinc foliar application at early stage of maize growth on the patterns of nutrients and dry matter accumulation by the caopy*. Part II. *Nitrogen uptake and dry matter accumulation patterns*. J. Elem., 13(1): 29-39.

Hong W., Ji-yun J. 2007. *Effects of zinc deficiency and drought on plant growth and metabolism of reactive oxygen species in maize (Zea mays* L.*)*. Agr. Sci. China, 6(8): 988-995.

Hossain M.A., Jahiruddin M., Islam M.R., Mian M.H. 2008. *The requirement of zinc for improvement of crop yield and mineral nutrition in the maize-mungbean-rice system*. Plant Soil, 306: 13-22.

Kalayci M., Torun B., Eker S., Aydin M., Ozturk L., Cakmak I. 1999. *Grain yield, zinc efficiency and zinc concentration of wheat cultivars grown in a zinc-deficient calcareous soil in field and greenhouse*. Field Crops Res., 63: 87-98.

Kaniuczak J., Hajduk E., Właśniewski S. 2009*a*. *The influence of liming and mineral fertilization on manganease and zinc content in potato tubers and green mass of pasture sunflower cultivated in loessial soil*. Zesz. Probl. Post. Nauk Rol., 541: 199-206. (in Polish)

Kaniuczak J., Właśniewski S., Hajduk E., Nazarkiwicz M. 2009*b*. *The influence of liming and mineral fertilization on manganease and zinc content in grain of winter wheat and spring barley cultivated in lessal soil*. Zesz. Probl. Post.Nauk Rol., 541: 207-215. (in Polish)

Kizilgoz I., Sakin E. 2010. *The effects of increased phosphorus application on shoot dry matter, shoot P and Zn concentrations in wheat (Triticum durum* L.*) and maize (Zea mays* L.*) grown in calacereous soil*. Afr. J. Biotechnol., V 9(36): 5893-5896.

Kutman U.B., Yildiz B., Cakmak I. 2011. *Improved nitrogen status enhances zinc and iron concentrations both in the whole grain and endosperm fraction of wheat*. J. Cereal Sci., 53: 118-125.

Mousavi D.R. 2011. *Zinc in crop production and interaction with phosphorus*. Aust. J. Basic Applied Sci., 5(9): 1503-1509.

Oury F.X., Leenhardt F., Rémésy C., Chanliaud E., Duperrier B., Balfourier F., Charmet G. 2006. *Genetic variability and stability of grain magnesium, zinc and iron concentrations in bread wheat*. Eur. J. Agron., 25: 177-185.

Potarzycki J. 2010. *The impact of fertilization systems on zinc management by grain m*aize. Fertilizers and Fertilization, 39: 78-89.

Potarzycki J., Grzebisz W. 2009. *Effect of zinc foliar application on grain yield of maize and its yielding components*. Plant Soil Environ., 55(2): 519-527.

Sadeghzadeh B. 2013. *A review of zinc nutrition and plant breeding*. .J. Soil Sci. Plant Nutr., 13 (4): 905-927

Salimpour S., Khavazi H., Nadian H., Besharati H., Miransari M. 2010. *Enhancing phosphorus availability to canola (Brassica napus* L.*) using P solubilizing and sulfur oxidizing bacteria*. Aust. J. Crop Sci., 4(5): 330-334.

Schulte E., Kelling K. 2000. *Plant analysis: A diagnostic tool*. University of Wisconsin-Madison. Available online at: www.ces.pardue.edu/extmedia/NCH/NCH-46.html

SPIAK Z. 1996. *Effect of the chemical form of zinc on their uptake by plants*. Zesz. Probl. Post. Nauk Rol., 434:997-1003. (in Polish)

STAIN A.J. 2009. *Global impacts of human mineral nutrition*. Plant Soil, 335: 133-154.

SUBEDI K., MA B. 2005. *Nitrogen uptake and partitioning in stay-green and leafy maize hybrids*. Crop Sci., 45: 740-747.

WESTAGE M., LIZASO J., BATCHELOR W. 2003. *Quantitative relationships between pollen shed density and grain yield of maize*. Crop Sci., 43: 934-942.

WHO 2002. *World Health Report. Reducing risks promoting healthy life*. http://www.who.int/whr/2002/en/whr02.en.pdf (retrived 13.07.2010)

WROŃSKA M., GRZEBISZ W., POTARZYCKI J., GAJ R. 2007. *Maize response to nitrogen and zinc fertilization. Part II. Accumulation of nutrients at maturity*. Fragm. Agron., 24, 2(94): 400-407. (in Polish)

YANG X.W., TIAN X.H., LU X.C., CAO Y.X., CHEN Z.H. 2011. *Impacts of phosphorus and zinc levels on phosphorus and zinc nutrition and phytic acid concentration in wheat (Triticum aestivum* L.*)*. J. Sci. Food Agric., 91: 2322-2328.

ZHANG F., ROMHELD V., MARSCHNER H. 1991. *Release of zinc mobilizing root exudates in different plant species as affected by zinc nutrition status*. J. Plant Nutr., 14: 675-686.

ZHANG Y., PANG L., YAN P., LIU D., ZHANG W., YOST R., ZHANG F., ZOU CH. 2013. *Zinc fertilizer placement affects zinc content in maize plant*. Plant Soil, 372: 81-92.

ZHAO F.J., SHEN Z.G., MCGRATHH S.P. 1998. *Solubility of zinc and interactions between zinc and phosphorus in the hyperaccumulator Thlaspi caerulescens*. Plant Cell Environ., 21: 108-114.

Załącznik 2

Krzysztof Bąk
Poldanor SA
ul. Dworcowa 25
77-320 Przechlewo
krzysztof.bak@poldanor.com.pl

Poznań, 10.08.2016

Oświadczenie

Oświadczam, że mój udział w pracach składających się na jednolity cykl publikacji stanowiących rozprawę doktorską dotyczył:

A1 - *kod udziału*: 1, 2, 4, 5,6,7 łącznie: [70%]
A2 - *kod udziału*: 1,2,4,5,6, 7 łącznie [52%]
A3 - *kod udziału*: 1, 4, 5, 6 łącznie [40%]
A4 - *kod udziału*: 1, 2, 4, 5,6,7 łącznie [52%]

---

*kod oznaczający udział współautora w opracowaniu artykułu
1 – inicjator tematyki ; 2 autor tematyki; nadzór naukowy nad eksperymentem; 4 wykonanie - redakcja publikacji; eksperymentu; 5 analiza wyników; 6- opracowanie syntezy; 7 redakcja publikacji; 8 – weryfikacja wyników; 9 – obliczenia statystyczne

dr Anna Budka
Katedra Metod Matematycznych
i Statystycznych
Wydział Rolnictwa i Bioinżynierii
Uniwersytet Przyrodniczy w Poznaniu
ul. Wojska Polskiego 28
60-637 Poznań

Poznań, 10.08.2016

Oświadczenie

Oświadczam, że mój udział w pracach składających się na jednolity cykl publikacji stanowiących rozprawę doktorską mgr inż. Krzysztofa Bąka polegał na niżej wymienionych działaniach:

A2 – *kod udziału*: 8,9: łącznie [15%]
43 - *kod udziału:* 8,9 : łącznie [15%]
A4 - *kod udziału:* 8,9: łącznie [18%]

Anna Budka

*kod oznaczający udział współautora w opracowaniu artykułu
1 – inicjator tematyki ; 2 autor tematyki; nadzór naukowy nad eksperymentem; 4 wykonanie - redakcja publikacji; eksperymentu; 5 analiza wyników; 6- opracowanie syntezy; 7 redakcja publikacji; 8 – weryfikacja wyników; 9 – obliczenia statystyczne

dr hab. Renata Gaj
Katedra Chemii Rolnej i Biogeochemii Środowiska
Wydział Rolnictwa i Bioinżynierii
Uniwersytet Przyrodniczy w Poznaniu
60-625 Poznań
ul. Wojska Polskiego 71F

Poznań, 10.08.2016

Oświadczenie

Oświadczam, że mój udział w pracach składających się na jednolity cykl publikacji stanowiących rozprawę doktorską dotyczył:

A1 – *kod udziału*	3, 5, 8	łącznie: [30%]
A2 – *kod udziału*	3,5, 8	łącznie: [33%]
A3 - *kod udziału*	1, 3, 5, 6, 7, 8	łącznie: . [45%]
A4 - *kod udziału*	3, 5, 8	łącznie: [30%]

*kod oznaczający udział współautora w opracowaniu artykułu
1 – inicjator tematyki ; 2 autor tematyki; 3 nadzór naukowy nad eksperymentem; 4 wykonanie eksperymentu; 5 analiza wyników; 6- opracowanie syntezy; 7 redakcja publikacji; 8 – weryfikacja wyników; 9 – obliczenia statystyczne

Ocena stanu odżywienia i poziomu plonowania kukurydzy (*Zea mays* L.) w warunkach zróżnicowanego nawożenia mineralnego

Kukurydza spośród uprawianych zbóż posiada największy potencjał plonotwórczy, którego podstawowym warunkiem realizacji jest stanowisko bogate fosfor i potas, a także inne składniki mineralne. Roślina ta wykazuje dużą wrażliwość i zmienność na zaopatrzenie w składniki pokarmowe w okresie wegetacji. Optymalne odżywienie roślin uprawnych w krytycznych fazach wzrostu jest jednym z najważniejszych czynników realizacji ich potencjału plonotwórczego. Aktualny stan wiedzy w zakresie reakcji kukurydzy na zaopatrzenie w fosfor i potas pozwolił na sformułowanie następującego problemu badawczego: czy *stosowanie zróżnicowanego nawożenia mineralnego fosforem i potasem ma istotny wpływ na stan odżywienia kukurydzy w fazach krytycznych, kształtowanie wielkości plonu oraz zawartość i akumulację składników w fazie dojrzałości fizjologicznej?*.

Celem podjętych badań była ocena stanu odżywienia kukurydzy w fazach krytycznych (BBCH 17, BBCH 65) oraz wielkości plonu rozważana w aspekcie dawki optymalnej składników mineralnych aplikowanych w nawozach oraz zredukowanego poziomu nawożenia fosforem i potasem.

Sformułowano następujące pytania szczegółowe:

1. Czy istnieje zależność pomiędzy stanem odżywienia kukurydzy w fazach krytycznych (przypadających na fazę 7-8 w pełni rozwiniętych liści oraz początek kwitnienia), a plonem ziarna kukurydzy w warunkach zróżnicowanego nawożenia mineralnego fosforem i potasem?
2. Czy zróżnicowane nawożenie mineralne P i K wpływa na gospodarkę makro i mikroskładników w roślinie w okresie wegetacji?
3. Czy kukurydza wykazuje rekcję plonotwórczą i żywieniową na formę fosforu aplikowaną w nawozie mineralnym?
4. Jak należy gospodarować fosforem i potasem w glebach o średniej zasobności w fosfor i potas przyswajalny, w warunkach intensywnej produkcji, uproszczonego zmianowania, aby uzyskać stabilny plony ziarna kukurydzy?

Aby zrealizować postawiony cel pracy przeprowadzono pięcioletnie badania polowe z kukurydzą odmiany *Veritis*. Doświadczenie jednoczynnikowe, stanowiło kontynuację wieloletniego eksperymentu założonego w 2000 roku, metodą bloków losowanych kompletnych. Czynnikiem badanym były zróżnicowane dawki fosforu i potasu przy stałym poziomie nawożenia azotem i magnezem. W trakcie wegetacji dwukrotnie dokonano oceny stanu odżywienia roślin w oparciu o wartości graniczne opracowane przez SCHULTE, KELLING (2000). W fazie dojrzałości fizjologicznej określono plon, zawartość i akumulację składników w organach wegetatywnych oraz wyznaczono indeksy akumulacji ocenianych makro i mikroskładników.

Uzyskane rezultaty badań zostały przedstawione w 4 oryginalnych pracach twórczych i dodatkowo uzupełnione o wyniki otrzymane w przeprowadzonym eksperymencie, które nie zostały ujęte w opublikowanych pracach. Zaprezentowane wyniki badań stanowią odpowiedź na postawiony problemy badawczy i pytania szczegółowe sformułowane przed rozpoczęciem eksperymentu polowego.

Przeprowadzone badania pozwoliły na sformułowanie następujących wniosków:

1. Ocena stanu odżywienia kukurydzy w fazie 7-8 liści (BBCH17) wykazała stan niedożywienia roślin wszystkim analizowanymi składnikami mineralnymi, z wyjątkiem żelaza, którego zawartość kształtowała się powyżej dolnej wartości normatywnej. Zróżnicowane dawki fosforu i potasu istotnie różnicowały w początkowym stadium rozwoju kukurydzy jedynie koncentrację miedzi i manganu w liściach.
2. Odnotowano istotną zależność pomiędzy stanem odżywienia kukurydzy w fazie 7 w pełni rozwiniętych liści właściwych a plonem ziarna. Analiza regresji wykazała, że plon ziarna niezależnie od obiektu determinowany był przez zawartość składników w liściach kukurydzy w zakresie od 59% do 94%.
3. W drugiej ocenianej fazie krytycznej przydającej na stadium kwitnienia roślin wykazano, że rośliny wykazały stan niedożywienia azotem, fosforem, magnezem, cynkiem i miedzią. Czynnik doświadczalny istotnie różnicował zawartość wapnia, magnezu, cynku i miedzi w liściu podflagowym. Pod wpływem nawożenia mineralnego stwierdzono wzrost zawartości N, P, K i Mn w liściach kukurydzy na wszystkich analizowanych obiektach, natomiast nie zanotowano istotnych różnic pomiędzy badanymi wariantami, na których zastosowano nawożenie mineralne. Wykazano również silną istotną zależność plonu od z zawartość składników w liściach w fazie kwitnienia kukurydzy, którą potwierdzają wyoskie wartości współczynników determinacji kształtujące się w przedziale od 74 do 95%.
4. Zróżnicowane dawki fosforu i potasu w warunkach prowadzonego doświadczenia istotnie kształtowały wielkość plonu ziarna kukurydzy. Działanie czynnika doświadczanego nie było jednoznaczne i wykazało dużą zmienność w latach badań. Kukurydza reagowała większą redukcją plonu ziarna na brak nawożenia fosforem niż potasem.

5. Ocena zależności plonu ziarna kukurydzy od stosunku N:K w fazach krytycznych wykazała wyższą wartość prognostyczną niż zależność plonu od pojedynczych zawartości analizowanych składników. Optymalny stosunek N:K niezależnie od badanego obiektu kształtował się w zakresie 1,5-2 i gwarantował uzyskanie plonu ziarna na poziomie 8t ha^{-1}.

6. Brak reakcji plonotwórczej i żywieniowej kukurydzy na formę nawozu fosforowego jednoznacznie wskazuje na zbliżone działanie plonotwórcze superfosfatu i częściowo zakwaszonego fosforytu jako nośników fosforu dla kukurydzy.

7. System gospodarowania fosforem i potasem w uprawie kukurydzy na glebie o średniej zasobności, polegający na dostarczeniu składników w ilości równej wyniesieniu ich z plonem ziarna w dłuższym przedziale czasu prowadzi do: (1) nadmiernego zubożenia gleby w przyswajalne formy składników, (2) niedożywienia roślin w trakcie wegetacji; (3) zakłócenia homeostazy żywieniowej, a w konsekwencji jest przyczyną redukcji plonu i spadku produktywności stanowiska.

8. Analizy chemiczne gleb po zakończeniu badań w 2011r. wskazują, że w wariantach nawożonych fosforem i potasem w porównaniu do roku 2007 stwierdzono spadek zawartości P i K przyswajalnego w glebie, który w porównaniu do roku 2007 wynosił odpowiednio 15,6% (43,2 mg P kg^{-1}) i 13,8% (97,4 mg K kg^{-1}).

Abstract

Evaluation of maize (*Zea mays* L.) nutritional status and yield levels under different mineral fertilization rates

Amongst all cultivated cereals, maize has the highest yield potential, which can be essentially achieved under conditions of the site with high availability of phosphorus and potassium, in addition to other mineral nutrients. Maize indicates high sensitivity and changeability in terms of requirements for nutrients during its growth period. The optimal nutrition of crops at the critical growth stages is one of crucial prerequisites for realization of their yield potential. Up to date knowledge on maize response to phosphorus and potassium supply allowed to define the following research problem: *does phosphorus and potassium mineral fertilization significantly affect the nutritional status of maize at the critical growth stages, as well as yield and nutrient concentration and accumulation at the stage of physiological maturity*?

The goal of the study was to assess the nutritional status of maize at the critical growth stages (BBCH 17, BBCH 65) and yield obtained, in consideration of the optimal doses of mineral nutrients applied as fertilizers, including reduced rates of phosphorus and potassium. The following comprehensive questions were asked:

1. Does a relationship exist between the nutritional status of maize at the critical growth stages (7-8 unfolded leaves and the beginning of flowering) and maize grain yield, under the conditions of differentiated mineral fertilization with phosphorus and potassium?
2. Does differentiated P and K fertilization influence macro- and micronutrient management in the period of plant growth?
3. Does maize show nutritional and yield forming response to the form of phosphorus applied as a mineral fertilizer?
4. In view of intensive crop production and simplified rotation, how should phosphorus and potassium be managed in the soils with medium availability of these nutrients so as to achieve the stable maize grain yield?

To meet the research objectives, a 5-year-long field study was carried on maize variety *Veritis*. A single-factor experiment was conducted as the continuation of the long-term trial, established in the year 2000, with the use of the randomized complete block design. The factor investigated in the present study was the differentiated dose of phosphorous and potassium at constant rates of magnesium and nitrogen fertilization. During the vegetation period, there was twice assessed the nutritional status of maize and compared with the threshold values recommended by SCHULTE, KELLING (2000). At maize physiological maturity, there were determined yields as well as nutrient concentrations and accumulations in maize vegetative organs. At the same time, there were concluded accumulation indexes for the studied macro- and micronutrients.

The results obtained were presented in 4 creative publications. Additional (not published) data was included in the dissertation. The results of the study allowed for drawing the following conclusions:

1. The assessment of the nutritional status of maize at the stage of 7-8 unfolded leaves (BBCH17) showed maize malnutrition with regard to all the analyzed mineral nutrients, except for iron, the concentration of which was higher than the lower limit of the normative value. In the early maize growth stage, differentiated phosphorus and potassium rates significantly varied no more than copper and manganese concentrations in the leaves.

2. At the stage of 7-8 fully unfolded leaves, there was found a significant relationship between maize nutritional status and grain yield. Regression analysis showed that regardless of the fertilizer treatment applied, maize grain yield was determined by nutrient concentrations in the leaves, ranging from 59% to 94%.

3. In the second assessed maize critical growth stage (flowering), plants showed malnutrition with nitrogen, phosphorus, magnesium, zinc and copper. The experimental factor significantly varied the concentrations of calcium, magnesium, zinc and copper in the sub-flag leaf. In all the treatments tested, the concentrations of N, P, K and Mn were increased in maize leaves as a result of mineral fertilization, however, no significant differences between the fertilizer treatments were found. At the same time, there was observed a significant relationship between yield and leaf nutrient concentrations in flowering maize, that was confirmed by high values of determination coefficients, ranging from 74 to 95%.

4. Under the conditions of the present study, differentiated doses of phosphorus and potassium significantly affected the size of maize grain yield. The effect of the experimental factor was ambiguous and varied in the observation years. The lack of phosphorus fertilization caused maize yield reduction to a greater extent when compared to that observed in the treatment with no potassium applied.

5. The evaluation of the dependency of maize grain yield on N:K ratio at maize critical growth stages pointed toward its higher prognostic importance when compared to the analysis of concentrations of individual nutrients tested in the present study with regard to their relationships with maize yield. Irrespective of the treatments applied, the optimal N:K ratio to assure 8-9 t ha^{-1} grain yield was 1.65 - 2.

6. No nutritional and yield forming response of maize to the form of phosphorus fertilizer applied is evidently a sign of analogous activities of superphosphate and partially acidulated phosphate rock as phosphorus carriers for maize.

7. In the long-term perspective, the system of phosphorus and potassium management in maize cultivation on the soil with medium nutrient availability, which involves nutrient supply equal to nutrient quantity taken out with grain yield, leads to: (1) the impoverishment of the soil in terms of nutrient availability, (2) plant malnutrition during the vegetation period, (3) disturbances of nutritional homeostasis. Consequently, P and K management as such becomes the reason of reduction of yield and site productivity. Soil chemical analyses, carried out after termination of the present study (2011), showed the decrease of available P and K in the soil when compared to the year 2007 – 15.6% (43.2 mg P kg^{-1}) and 13.8% (97.4 mg K kg^{-1}), respectively.