Improving phosphorus use efficiency for snap bean production by optimizing application rate

G.D. Liu[1], K. Morgan[2], B. Hogue[1], Y.C. Li[3], D. Sui[4]

[1]*Horticultural Sciences Department, IFAS, University of Florida, Gainesville, USA*

[2]*Soil and Water Science Department, Southwest Florida Research and Education Center, IFAS, University of Florida, Immokalee, USA*

[3]*Soil and Water Science Department, Tropical Research and Education Center, IFAS, University of Florida, Homestead, USA*

[4]*Palm Beach County Cooperative Extension, IFAS, University of Florida, West Palm Beach, USA*

Abstract

Liu G.D., Morgan K., Hogue B., Li Y.C., Sui D. (2015): **Improving phosphorus use efficiency for snap bean production by optimizing application**. Hort. Sci. (Prague), 42: 94–101.

Phosphorus (P) is essential for crop production. Adequate application P rate is critical for enhancing productivity and profitability of snap bean (*Phaseolus vulgaris* L.). The goal of this study was to optimize P application rate for commercial snap bean production in south Florida. Six trials were conducted on sandy soils and muck soils in Hendry County and Palm Beach County, Florida, USA. Before planting cv. Caprice snap bean, plots were fertilized with different P application rates in the form of triple superphosphate (0-45-0). An increase in P_2O_5 application rates up to 134 kg/ha P_2O_5 significantly increased the marketable bean yields. However, beyond that point, significant field gains did not occur with further increased application. At 134 kg/ha P_2O_5, bean appearance quality was the best compared to the other treatments. These results indicate that 134 kg/ha P_2O_5 produced best bean appearance quality and was the optimum rate for commercial production of snap bean in high-pH soils in south Florida.

Keywords: *Phaseolus vulgaris*; optimum phosphorus rate; productivity; marketable bean yields; bean appearance quality

Florida is a leader in the P-fertilizer production industry and provides 75% of P fertilizers to the US and 25% to the world (Grego 2001). However, economically viable phosphate rock in Florida and over the world will be depleted in a few decades (Raghothama 1999; Cordell et al. 2009). Global P fertilizer shortages have already occurred and the Florida P fertilizer industry has begun importing P rock from Morocco and other countries (Abelson 1999; Cordell et al. 2009). Because only a few countries are relatively rich in P-rock resources, a new Organization of Phosphate Exporting Countries (OPEC) may arise in the near future (Epstein, Bloom 2005). This depletion of P mineral resources requires growers to modify current agricultural practices to use P fertilizers more efficiently than ever before.

The ecological concern about the negative impacts of P enrichment on the environment is the second motivating factor. There is a natural region of tropical wetlands in southern Florida, the Everglades, one of the world's most important wetland ecosystems.

Because the Everglades is extremely oligotrophic, the U.S. Environmental Protection Agency (USEPA) has determined that annual and/or long-term P concentration needs to be less than 10 parts per billion (ppb) to protect native flora and fauna (Payne et al. 2003). However, P concentrations of ground water in the Everglades have been as high as 600 ppb in the wet season but only 10 ppb in the dry season (Muñoz-Carpena et al. 2005). As a nonpoint source of pollution, crop production contributes to the high P concentrations in these waterways. To protect the environment from excessive P and vegetation shifts (e.g. cattail replacing sawgrass in the Everglades (McCormick et al. 2009)), optimizing P management in agricultural is crucial.

While ecology and P mineral source availability both point to the reduction in P fertilizer application rates, economics is the key factor for us to maximize P use efficiency in crop production. According to the United States Department of Agriculture (USDA) National Agricultural Statistics Service (USDA 2012), fertilizer prices have escalated by approximately 500% since 2000, while market prices of snap beans have only increased by 50% (Fig. 1). This divergent trend of production costs and market prices of snap beans is attributed to different reasons: (1) an increase in fertilizer costs due to globally rising energy prices and (2) US food policy of keeping the price of food as low as possible. Therefore, snap bean growers are forced to operate on increasingly thinner profit margins, making the efficient use of P imperative to achieve long-term profitability.

Snap bean is a major vegetable crop in the United States. Florida ranks first in production, acreage, and total value of fresh market in the nation (FDACS

2011; Elwakil, Mossler 2012). South Florida is the principal region of snap bean production in the state. Fertilization is critical for growing snap bean in this region because sandy soils are water repellent and poor at holding water and nutrients (Hallett 2008; Hall 2009). Once P fertilizers are applied to the soil, they have one of four fates: plant uptake, soil fixation, runoff, and leaching. Phosphorus uptake by snap bean has been reported to be as high as 17.9 kg/ha at bean yields of 11,200 kg/ha (Maynard, Hochmuth 2013). In Florida, snap bean yields are usually lower than 11,200 kg/ha. Therefore, the P uptake by snap bean was expected to be less than 17.9 kg/ha. Phosphorus that is not utilized by plants can cause eutrophication problems in surrounding ecosystems, the Everglades.

For selected plant nutrients, the University of Florida – Institute of Food and Agricultural Sciences (UF/IFAS) has developed a range of nutrient specific soil concentrations into classifications called indices of very low, low, medium, high and very high using data collected in field (Olson et al. 2011; Hochmuth, Hanlon 2013). The developed range of nutrient concentrations in the soil is based on the response of the crop growth and yields to a wide range of nutrient fertilizer applications in a large number of field studies. However, these indices were developed for the acidic sandy soils that typify Florida agriculture. Use of these indices have proved to be problematic in south Florida where sandy soils have increased in pH with continuous production (Sato et al. 2008). Particularly, in muck soil, soil pH can gradually increase with time because the organic matter decomposes and muck subsidence causes proximity to the underly-
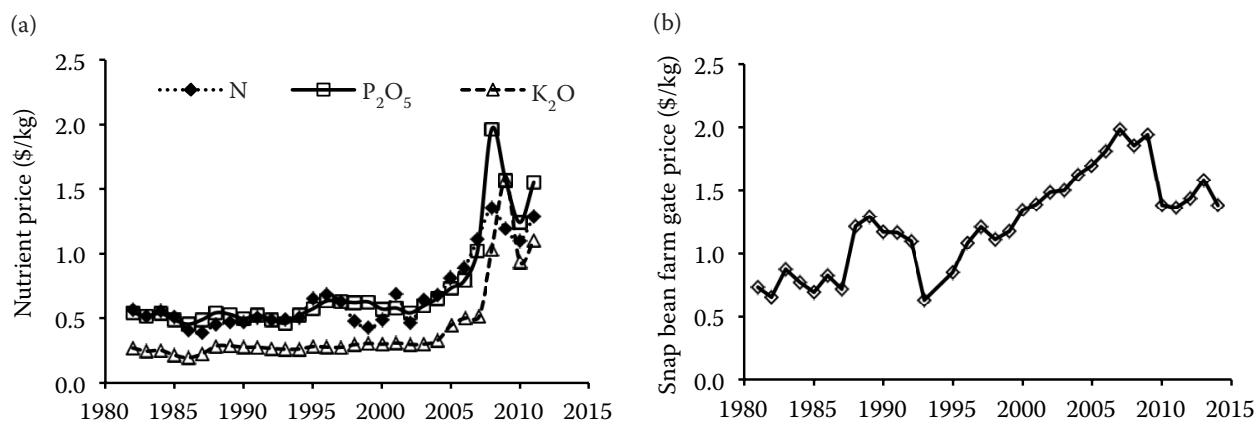
(a)

(b)

Fig. 1. Changes in fertilizer prices for Freight on Board (a) and in the farm gate snap bean price (b) during last 30 years from 1982 to 2011 (USDA 2012)

ing calcareous material (Liu et al. 2013). Likewise, indices for vegetable production on soil with high levels of organic matter such as muck soil have not been developed. To ensure P-use efficiency and enhance economic and ecological sustainability, the UF/IFAS recommends a P rate for snap beans from 90 to 134 kg/ha, based on the P bioavailability index of medium (i.e. 30 mg/l or less) in Florida acidic sandy soils (Hochmuth, Hanlon 2013). However, producers have traditionally applied P fertilizers in excess as a means of insuring adequate soil P concentrations for their crops. Current practices use 224.0 kg/ha on commercial vegetable farms in south Florida (personal communication with local farmers). The objective of this study was to optimize P fertilizer application rates for commercial snap bean production in south Florida.

MATERIAL AND METHODS

Two sets of studies were conducted. The first set was performed at two farms with high pH soils (pH > 7.0) and initial extractable soil P exceeding the medium index to investigate the response of biomass and yield to added fertilizer P. The second set was conducted to determine the response of snap bean plants to P_2O_5 rates and optimize P application rate.

Hendry County. Studies were initiated at two farms in eastern Hendry County, Florida from September 2008 to May 2010 on sandy, poorly drained Spodisols classified as Immokalee fine sand (Sandy, siliceous, hyperthermic Arenic Alaquods). The first farm was located at latitude 26°26'58.98"N, longitude 80°58'54.06"W and second farm was at latitude 26°28'59.65"N, longitude 80°58'54.26"W. The same blocks were used twice at each farm. Two crops planted at the first farm were grown from October 23 to December 12, 2008 (Henry 1) and February 12 to April 25, 2010 (Henry 2). The initial Mehlich III (Sims 1989) extractable soil P was 57 and 81 mg/kg for the two trials, respectively, with a pH of 7.3 ± 0.1. Two additional crops of snap bean were grown at the second farm from February 28 to May 3, 2009 (Henry 3) and March 12 to May 10, 2010 (Henry 4). Initial Mehlich III extractable soil P was 87 and 63 for the two trials, respectively, with a soil pH of 7.1 ± 0.1. Four rates (0, 45, 67, and 90 kg/ha) of phosphate fertilizer as triple superphosphate were used at each site. Each plot was 6 rows wide and 150 to

210 m long depending on field location. Row spacing was 76.2 cm while in-row spacing was 5.1 cm accounting for 258,325 seeds/ha. The P fertilizer was applied and incorporated in the soil during the pre-bedding and bedding operation. With the exception of four selected P rates the other fertilizer rates (kg/ha) and practices were: N as ammonium nitrate, 90.1, pre-planting broadcasting: 12.3; at seeding, 24.6; 25 days after seeding: 53.2; K as potassium chloride, pre-planting broadcasting: 137.8; Mn as manganese sulfate, 2.4; Zn as zinc sulfate, 1.7; Cu as copper sulfate, 1.7; B as borax, 1.7; and all of K; all of the micronutrients were evenly foliar-applied at bud and pin stages.

Biomass accumulation at harvest was determined by cutting plant stems above the soil surface. Marketable bean pods as yield were removed from the cut plants and weighed fresh in the field (USDA 2002). The entire shoot (the above ground portion of the plant) was then dried 65°C with ventilation until constant weights are reached. The stems and leaves were separated before drying and weighed. Biomass and yield was determined using three 3-m lengths of single row sub-samples for snap bean within each plot.

Palm Beach County. Two trials were conducted on two commercial farms in Palm Beach County, Florida. The first trial was conducted from November 21, 2011 to February 1, 2012 at latitude 26°42'59.36"N, longitude 80°50'42.46"W. The soil in this farm is muck soil (Typic Haplohemists, euic, hyperthermic) with a pH of 6.0 ± 0.1. The second trial was conducted from March 1 to April 27, 2012 at latitude 26°48'16.12"N, longitude 80°26'31.26"W near the west bank of L8 Canal in the county. The soil is fine sand (Arenic Umbric Endoaqualfs, loamy, siliceous, active, hyperthermic) with a pH of 6.5 ± 0.1. Field management practices at each site were identical to the current procedures used by local snap bean producers (Olson, Simonne 2007). A randomized complete block design was applied using 56 m² plots consisting of eight 9.1 m rows each with four replicates. Row spacing was 76.2 cm while in-row spacing was 5.1 cm accounting for 258,325 seeds/ha. A commercial cultivar (Caprice) was grown with P rates of 0, 45 k, 90, 134, 179, 224, and 269 kg/ha P_2O_5 in the form of triple superphosphate (0-45-0) applied prior to planting. At harvest, the central 6.1 m of central rows 4 and 5 were harvested in each plot, accounting for a total of 9.3 m² harvested in each plot. Marketable beans

were harvested with weights measured, while bean length and diameter from 30 randomly selected beans were determined with a ruler and a caliper in the second trial. At the same time, four plants per plot were randomly collected for P concentration and biomass measurements of the stems, leaves, and beans for individual plants.

Tissue and soil analysis. Biomass tissue samples for all studies were based on an ash digestion method by HANLON et al. (1994). Briefly, 200 mg of oven-dry (65°C for 5 days) plant tissue was placed in a muffle furnace at 550°C for 4 hours. The resulting ash was dissolved with 2.25 ml 6.0M hydrochloric acid (HCl), filtered through a Whatman No. 41 filter paper (VWR LabShop, Batavia, USA), and diluted to volume in a 50 ml volumetric flask with double deionized water. Soil samples from all studies were analysed for soil extractable P content using the Mehlich III [1:10 (w:v)] method (SCHRODER et al. 2009) and analysed using an Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES, Perkin Elmer, Waltham, USA) (MUNTER et al. 1984) for the Hendry County studies and an Automated Discrete Analyser (AQ2+; SEAL Analytical, Hanau, Germany) based on USEPA Method 365.1 (U.S. Environmental Protection Agency 1993) for the Palm Beach County studies. Phosphorus accumulation was calculated based on P concentration and biomass of the plant tissues.

Data analysis. Data were analysed using one-way ANOVA method (SAS Institute 2009), the critical ranges ($LSD_{2, 0.05}$) of Duncan's Multiple Range Test were used to detect the difference significance between two means (HUBBARD 2001).

RESULTS AND DISCUSSION

In Hendry County, both biomass and yield increased with added P rate (Fig. 2). Biomass and yield were both the highest values for most of the trials at 90 kg/ha but Henry 2 had the max. shoot biomass at 67 kg/ha and Henry 3 produced the max. bean yield also at 67 kg/ha. Among the four trials, Henry 4 was always on the top for both shoot biomass and bean yields but Henry 1 was always at the bottom for bean yields even though its shoot biomass were always the second greatest. These differences might be possibly attributed to the changes in carbon partitioning among the trials due to climatic and edaphological reasons.

In Palm Beach County, bean yields were increased with added P. Significant gains in bean yield were observed for both locations at Lake Harbor and Belle Glade with increasing P_2O_5 application rate from 0 to 134 kg/ha P_2O_5. Beyond the application rate of 134 kg/ha P_2O_5, neither site measured significantly increases (Fig. 3). This difference of bean yields observed from 134–269 kg/ha P_2O_5 were more likely due to the difference of the plant available P between the two different soils. The Mehlich III extractable P concentration before planting was 82.3 ± 5.7 ppm in the muck soil samples (Lake Harbor) and was 37.8 ± 1.9 ppm in the fine sand soil (Belle Glade). Marketable bean yield was greater in the muck soil than in the fine sand soil (Fig. 3). Based on the bean yield trial data from both sites, 134 kg/ha P_2O_5 was the optimum application rate for snap bean productivity.
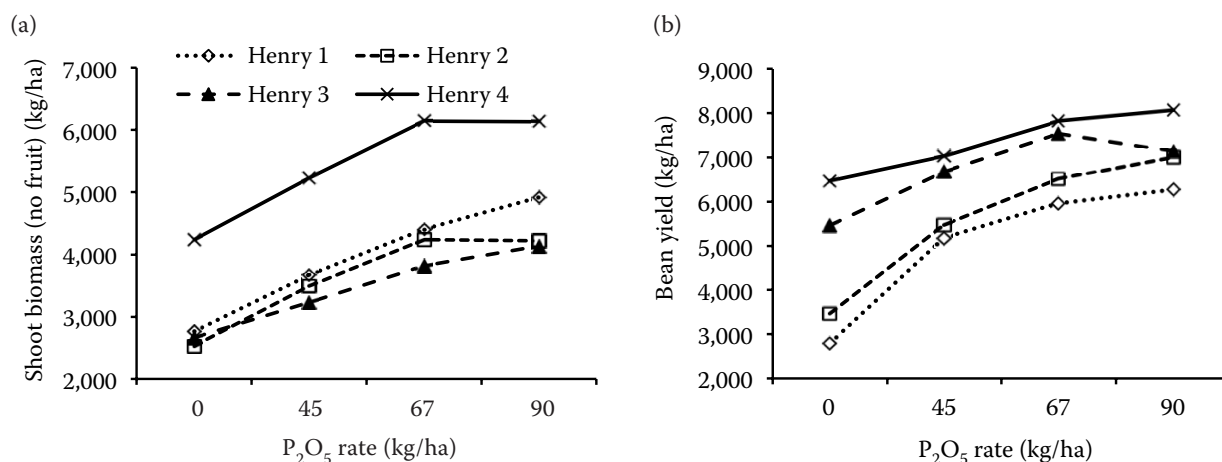

Fig. 2. Snap bean biomass accumulation (a) and relative marketable yields (b) at different P rates at the farms near Clewiston; October 23 to December 12, 2008 (Henry 1) and February 12 to April 25, 2010 (Henry 2) and at the Thomas Produce site; February 28 to May 3, 2009 (Henry 3) and March 12 to May 10, 2010 (Henry 4) near Clewiston, Florida
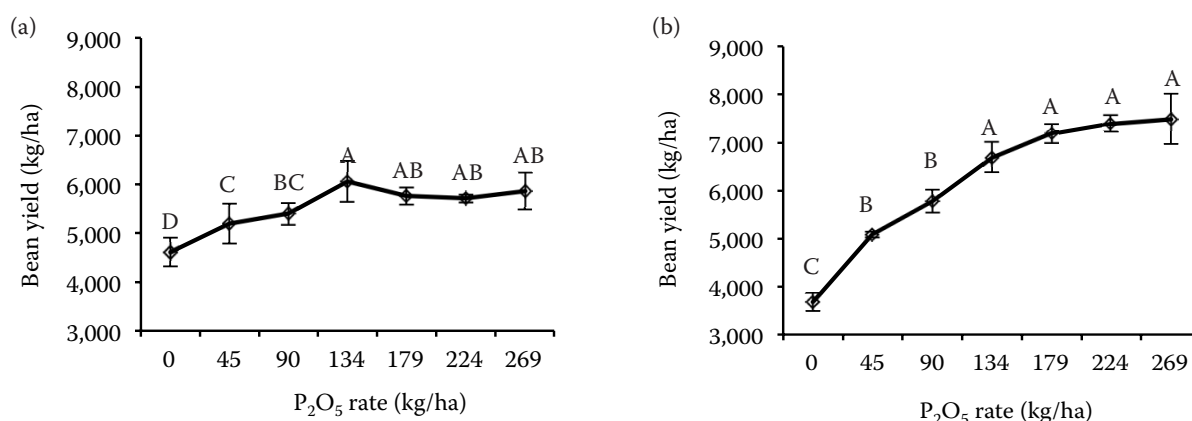
Fig. 3. Snap bean marketable yields at different P rates (a) in Lake Harbor, Florida from November 21, 2011 to February 1, 2012 and (b) in Belle Glade, Florida from March 1 to April 27, 2012. The yields of the both trials followed a saturation law. P rate of 134 kg/ha P_2O_5 was the best

$P = 0.05$, $LSD_{2, 0.05} = 459$ kg/ha for Lake Harbor, Florida and $P = 0.05$, $LSD_{2, 0.05} = 876$ kg/ha for Belle Glade, Florida; data points sharing the same letter indicate they are not significantly different

Phosphorus concentrations measured in the plant tissues of snap bean were relatively consistent across all P_2O_5 treatments excluding the control without P application. Similarly, the concentrations and proportions of P in beans, leaves, and stems were not significantly different (Fig. 4). Absorption of P by snap bean plants was not significantly different across most treatments, when excluding the control (0 kg/ha P_2O_5). Bean plants fertilized at both sites contained approximately 24.0 to 34.6 kg/ha P_2O_5. There was a decrease in plant absorbed P_2O_5 at the highest application rate in Lake Harbor, Florida. These results were similar to previous results in Florida (Maynard, Hochmuth 2013). The plants of the controls, however, absorbed P_2O_5 less than 16.2 and 16.6 kg/ha P_2O_5 for Lake Harbor and Belle Glade, respectively, indicating while P fertilization is critical for snap bean growth in these sites, more than half of available P utilized was already present before fertilization. In other words, only 7% (in a range from 2 to 17% in Lake Harbor) to 12% (in a range from 7 to 25% in Belle Glade) of P fertilization contributed to P accumulation in plant tissues. These data imply that there is much room for improvement regarding growers using P fertilizer efficiency in snap bean production. As a means of improving efficiency and long-term sustainability of agricultural practices in South Florida, these data suggest a reduction from 224 kg/ha P_2O_5 (current grower application rates) to 134 kg/ha P_2O_5 (Fig. 3) would be appropriate.
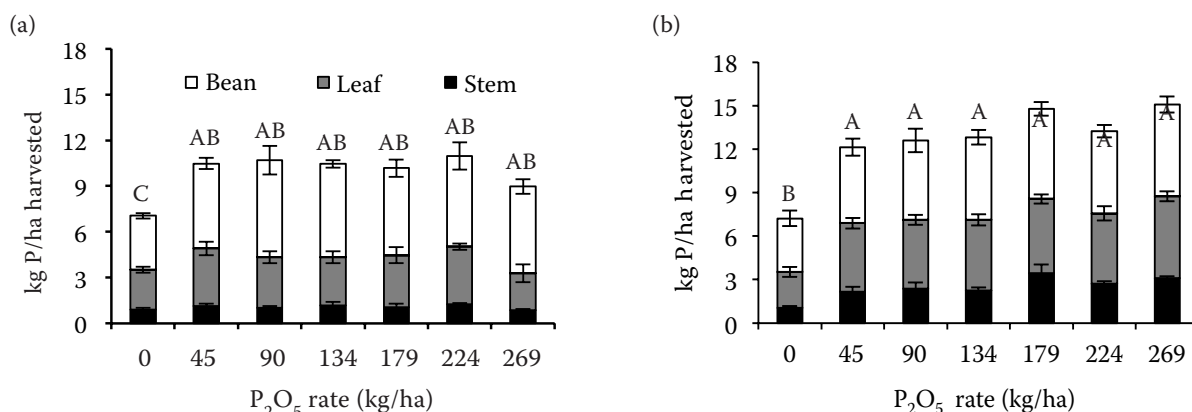

Fig. 4. P accumulation of snap bean at different P rates in (a) trial 1 in Lake Harbor, Florida from November 21, 2011 to February 1, 2012 and (b) trial 2 in Belle Glade from March 1 to April 27, 2012

$P = 0.05$, $LSD_{2, 0.05} = 4.0$ kg/ha for Lake Harbor, Florida and $P = 0.05$, $LSD_{2, 0.05} = 7.1$ kg/ha for Belle Glade, Florida; histograms sharing the same letter indicate they are not significantly different
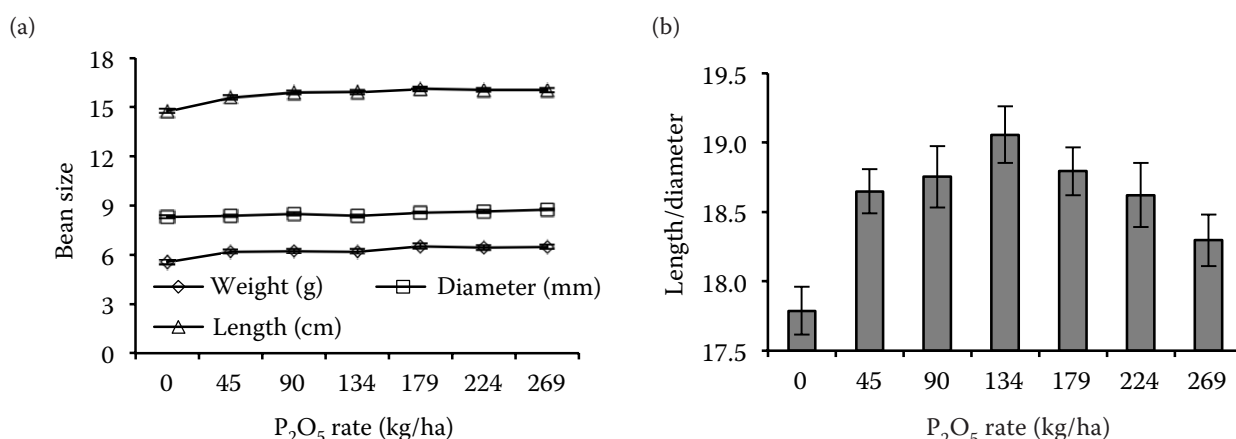
Fig. 5. Changes in bean size (a) and ratio (b) of bean length to bean diameter value of beans at different phosphorus application rates in Belle Glade from March 1 to April 27, 2012

Total P accumulation (kg/ha) in snap bean plants grown in Belle Glade and in Lake Harbor was 7.1 and 7.2; 10.5 and 12.1; 10.7 and 12.6; 10.5 and 12.8; 10.2 and 14.8; 11.0 and 13.2; and 9.0 and 15.1 for the fertilizer P rates (kg/ha P_2O_5) of 0; 45; 90; 134; 179; 224; and 269, respectively (Fig. 4). The plants grown in Belle Glade always had greater P accumulation than those grown in Lake Harbor. The respective difference (%) was 2.5; 15.9; 17.9; 22.7; 45.2; 20.7; and 68.4. These differences might be attributed to the shallow muck soil in Lake Harbor (Liu et al. 2013). This lower P accumulation in the Lake Harbor site may explain the little yield responses to P fertilization when P rates were greater than 134 kg/ha P_2O_5.

The IFAS recommendation for P fertilization is 0 for soils if the soil test shows high and very high P levels in soil and 90 to 134 kg/ha P_2O_5 if the soil

test indicates medium, low and very low P levels in the soil (Olson, Simonne 2007). The results of this research confirmed the IFAS recommendation. Fertilization based on the recommendation favours P use efficiency in agriculture significantly. The use efficiency of P fertilizers is related to soil property and hence soil P status (Antille et al. 2014). Obviously, to further increase P fertilizer use efficiency, more research on soil P status in the soils needs to be done in the near future.

The ratio of bean length to bean diameter (L/D value) is an important attribute for assessing bean appearance quality and is closely associated with bean length and width. Both bean appearance and weight increased with P fertilization increase while the bean length did not increase significantly when the P application rate was greater than 179.2 kg/ha
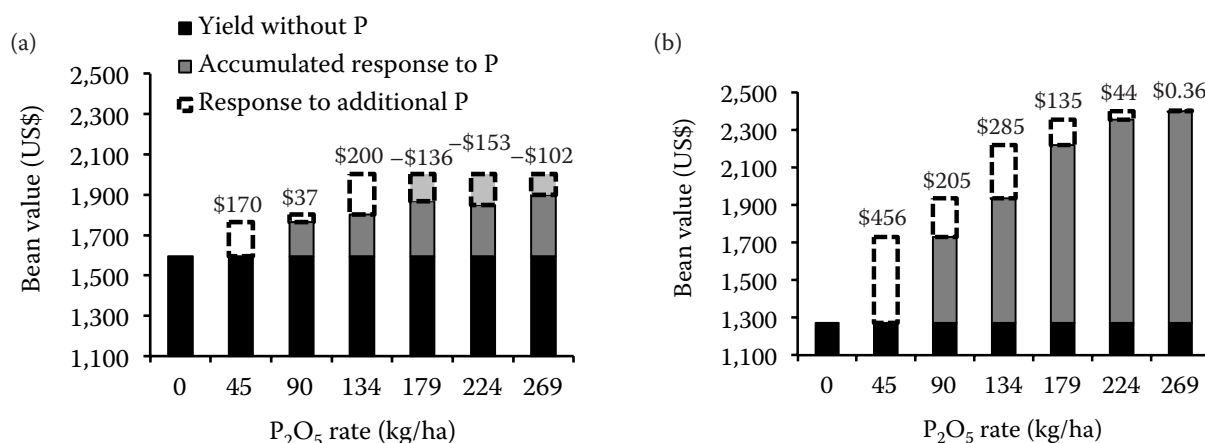

Fig. 6. Max. profit yield of snap bean at (a) Lake Harbor and (b) Belle Glade for different phosphorus application rates calculations were based on $664/t triple superphosphate and $0.76/kg for snap beans. Each dotted rectangle represents the gain or loss, accompanied with an increased P rate. The value is shown above and represents a change from the the greatest value from subsequent lower P rates

P_2O_5, suggesting a possible max. length of 16 cm. Bean diameter, however, was almost unresponsive to P treatments from 0 to 134 kg/ha P_2O_5 but then increased when the P applications was greater than 134 kg/ha P_2O_5 (Fig. 5a). The L/D value peaked at 134 kg/ha P_2O_5 (Fig. 5b), the best bean length/diameter ratio and the optimum P rate for the profitability are the same: 134 kg/ha P_2O_5.

It is important to sustainably produce max. bean yields with best bean appearance quality. Ultimately, the factors must be balanced with both the production cost for maximum profit and minimum environmental impact. The increased application of P_2O_5 at both sites increased overall yields if application rate is lower than 134 kg/ha P_2O_5, however, with the price of superphosphate being approximately \$665/t (USDA 2012), the increased cost of each treatment was \$28.91. This combination of the yield data and the 2011 value for beans (\$0.76/kg) (USDA 2012) reflects the max. yields and profit for each increment in approximately 45 kg/ha P_2O_5 (Fig. 6) more accurately.

It should be noticed that the control plots (0 kg/ha P_2O_5) produced greater bean yield at the Lake Harbor farm than at the Belle Glade farm (Fig. 3). However, the increase in profit yields for each level of increased P rate was greater at Belle Glade than at Lake Harbor. In particular, when the P rate was more than 134 kg/ha P_2O_5, the profit yields for Lake Harbor even decreased while that for Belle Glade still showed an increase (Fig. 6). These observations suggest significant differences in the soil at the two farms in Palm Beach County, with Lake Harbor being able to retain more P enabling higher yields at low P rates but also decreasing bean yields at higher P rates. While there were differences in overall profit yields between the two sites, both sites displayed a decreasing profit with increasing P application rates above 59 kg/ha P (Fig. 6). These observations suggest that in soils that retain P, lower P rate of approximately 134 kg/ha P_2O_5 is best while in soils where P is more readily available after being applied best P rates could vary between 134–224 kg/ha P_2O_5 (Fig. 6). No profit or economic loss calculation included possible environmental impacts.

CONCLUSION

Phosphorus fertilization is essential for snap bean production in south Florida. As available mineral resources decrease, the efficiency in P fertilizer use must be increased. Current application rates up to 224 kg/ha P_2O_5 are practiced in south Florida. Our studies in Henry County showed that increased fertilizer P_2O_5 rates from 0 to 90 kg/ha resulted in almost-consistent improvements in plant biomass and yields in the location. These results indicated that optimum rate was at or greater than 90 kg/ha. Additional P_2O_5 rate trials conducted in Palm Beach County showed that a further increasing percentage more than 134 kg/ha P_2O_5 was not utilized by the plants since the plant's nutrient requirement was satisfied. Bean length/diameter analysis showed that 134 kg/ha P_2O_5 produced the highest appearance quality beans. Phosphorus accumulation in non-fertilized and fertilized snap bean plants ranged from approximately 16.2 to 16.6 and 20.5 to 34.6 kg/ha P_2O_5 for the Lake Harbor and Belle Glade sites. These results indicated that P application rates greater than 134 kg/ha P_2O_5 did not produce significantly greater yields or quality snap beans; therefore the conclusion can be made that 134 kg/ha P_2O_5 was the best application rate with regards to profitability for commercial snap bean production in south Florida. Soil P status in the area needs to be further studied for maximizing in P use efficiency for the crop production.

References

Abelson P.H. (1999): A potential phosphate crisis. Science, 283: 2015.

Alva A.K., Obreza T.A. (1993): Variation in soil pH and calcium status influenced by microsprinkler wetting pattern for young citrus trees. HortScience, 28: 1166–1167.

Antille D.L., Sakrabani R., Godwin R.J. (2014): Effects of biosolids-derived organomineral fertilizers, urea, and biosolids granules on crop and soil established with ryegrass (*Lolium perenne* L.). Communications in Soil Science and Plant Analysis, 45: 1605–1621.

Cordell D., Drangert J.-O., White S. (2009): The story of phosphorus: Global food security and food for thought. Global Environmental Change, 19: 292–305.

Eckert D.J., Watson M.E. (1996): Integrating the Mehlich III extractant into existing soil test interpretation schemes. Communications in Soil Science and Plant Analysis, 27: 1237–1249.

Elwak W.M., Mossler M.A. (2012): Florida Crop/Pest Management Profiles: Snap Beans. Pesticide Information Office, Agronomy Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Available at http://edis.ifas.ufl.edu/pi032

Epstein E., Bloom A.J. (2005): Mineral Nutrition of plants: Principles and Perspectives. 2nd Ed. Sunderland, Sinauer Associates, Inc.

FDACS (2011): Florida Agricultural Crop Facts and Statistics Overview. Tallahassee, Florida Department of Agriculture and Consumer Services. Availabe at http://www.florida-agriculture.com/brochures/P-01304.pdf (accessed Aug 20, 2014).

Grego S. (2001): Phosphate Primer. Florida Industrial and Phosphate Research Institute. Available at http://www.fipr.state.fl.us/about-us/phosphate-primer/introduction-phosphate-as-an-essential-mineral/ (accessed April 21, 2015).

Hall D. (2009): Water repellence. Managing South Coast Sandplain soils to yield potential. Department of Agriculture and Food, Western Australia, Bulletin 4773: 48–63.

Hallett P.D. (2008): A brief overview of the causes, impacts and amelioration of soil water repellency: A review. Soil and Water Research, 3: S21–S29.

Hanlon E.A., Gonzalez J.S., Bartos J.M. (1994): Standard determination of Ca, Mg, P, K, Na, Mn, Cu, Fe, Zn, and B in plant tissue. In: Hanlon E.A. et al. (eds): IFAS Extension Soil Testing Laboratory Chemical Procedures and Training Manual. Cir 812. Gainesville, Florida Cooperative Extension Service, IFAS, University of Florida.

Hochmuth G., Hanlon E. (2013): A Summary of N, P, and K Research with Snap Bean in Florida. Available at http://edis.ifas.ufl.edu/cv234 (accessed Aug 20, 2014).

Hubbard M.R. (2001): Statistical Quality Control for the Food Industry. 2nd Ed. Caithersburg, Aspen Publishers, Inc.

Liu G.D., Simonne E.H., Hochmuth G.J. (2013): Soil and Fertilizer Management for Vegetable Production in Florida. Available at http://edis.ifas.ufl.edu/pdffiles/CV/CV10100.pdf (accessed Oct 2, 2014).

Liu G.D., Sui D., Li Y.C. (2012): Optimizing phosphorus rate for the sustainability of commercial snap bean production in South Florida. Proceedings of Florida State Horticutural Society, 125: 158–161.

Maynard D.N., Hockmuth G.J. (2013): Knott's Handbook for Vegetable Growers (5th Ed.). Hoboken, John Wiley & Sons, Inc.

McCormick P.V., Newman S., Vilchek L.W. (2009): Landscape responses to wetland eutrophication: loss of slough habitat in the Florida Everglades, USA. Hydrobiologia, 621: 105–114.

Muñoz-Carpena R., Ritter A., Li Y.C. (2005): Dynamic factor analysis of groundwater quality trends in an agricultural area adjacent to Everglades National Park. Journal of Contaminant Hydrology, 80: 49–70.

Munter R.C., Halverson T.L., Anderson R.D. (1984): Quality assurance for plant tissue analysis by ICP-AES. Communications in Soil Science and Plant Analysis, 15: 1285–1322.

Olson S.M., Simonne E. (2007): Vegetable Production Handbook for Florida 2006–2007. Gainesville, UF-IFAS.

Payne G., Bennett T., Weaver K. (2003): Development of a numeric phosphorus criterion for the Everglades Protection Area. Chapter 5. In: 2002 Everglades Consolidated Report. South Florida Water Management District, West Palm Beach.

Raghothama K.G. (1999): Phosphate acquisition. Annual Review of Plant Physiology and Plant Molecular Biology, 50: 665–693.

SAS Institute (2009): SAS/STAT User's Guide. Version 9.1.3. Cary, SAS Inst.

Sato S., Morgan K.T., Ozores-Hampton M., Simonne E.H. (2008): Spatial and temporal distributions in sandy soils with seepage irrigation: II. Phosphorus and potassium. Soil Science Society of America Journal, 73: 1053–1060.

Schroder J.L, Zhang H., Richards J.R. Payton M.E. (2009): Interlaboratory validation of the Mehlich III method as a universal extractant for plant nutrients. Journal of AOAC International, 92: 995–1008.

Sims J.T. (1989): Comparison of mehlich 1 and mehlich 3 extractants for P, K, Ca, Mg, Mn, Cu and Zn in atlantic coastal plain soils. Communications in Soil Science and Plant Analysis, 20: 1707–1726.

U.S. Environmental Protection Agency (1993): Methods for chemical analysis of water and wastes. Environmental Monitoring and Support Laboratory Cincinnati, OH, Report Number: EPA/600/R-93/100.

USDA (2002): Snap Bean: Shipping Point and Market Inspection Instructions. U.S. Standards for Grades of Snap Beans, Section 51.3829. Available at http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5098288

USDA (2012): Agricultural Prices. Available at http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26727 (accessed Aug 20, 2014).

Corresponding author:

Assist. Prof. Guodong Liu, IFAS, University of Florida, Horticultural Sciences Department,
1253 Fifield Hall, Gainesville, FL 32611, USA
phone: + 001 352 273 4814, e-mail: guodong@ufl.edu