ARIZONA STATE UNIVERSITY

SCHOOL OF SUSTAINABLE ENGINEERING AND THE BUILT ENVIRONMENT

CESEM

Center for Earth Systems Engineering and Management

# A Life Cycle Assessment of Phosphorous

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## Introduction

Phosphorus (P) is a non-renewable and indispensable resource for modern human society, sustaining the global food supply as a key nutrient for crop growth. However, human P usage is very inefficient. For example, about 80% of P mined for fertilizer but only 1.5% of that is consumed by humans and 46% is lost from soil erosion and runoff (Rittmann, 2011). Inefficient agricultural fertilization reflects P being fixed in the soil or washed out by run off into aquatic ecosystems, causing eutrophication. Meanwhile, concerns have been raised about the long-term availability of cheap phosphorus (Cordell et al. 2011, Elser and Bennett, 2011). For example, in 2007 to 2008, an alarming 700% P rock price increase that accompanied global food price escalation and worldwide unrest (Elser and Bennett, 2011). Thus, efforts have been urged to "close the human P cycle" by developing more P-efficient agricultural systems coupled to novel P fertilizers generated by recycling from waste streams (Childers et al., 2011).

One means of improving agricultural P efficiency involves genetic engineering strategies to increase crop use of soil P (Gaxiola, 2011). For example, Yang et al (2007) reported that crops transformed with the type I H+-pyrophosphatase (H+-PPase) AVP1 gene from Arabidopsis (*AtAVP1*OX) show enhanced root growth and more efficient scavenging of phosphate in P-poor soil. Gaxiola (2013) has also engineered romaine lettuce (*Lactuca sativa* cv. conquistador) and tomato (*Lycopersicon esculentum* Mill. cultivar Money Maker) to overexpress this AVP1 gene. However, most of the general public has a negative stereotype toward genetic modified (GM) crops. Part of the reason is because most of the GM crops in the market are chemical (herbicide, pesticide, fungicide etc.) resistant GM crops. Intensive application of chemicals can cause notorious environmental impacts. For instance, GM cotton in the U.S. is produced to be herbicide resistant to fight against weeds. However, years and years of applying herbicide, weeds evolved to become herbicide resistant. In addition to that, a lot of herbicide or pesticide contain phosphorus (P). Over applying them can also deteriorate down stream eutrophication. AVP1 GM crops are not chemical resistant. They are made to be nutrient use efficient. By applying them, we hope to reduce current P fertilizer usage but not compromise yield.

There are quite a few of LCA researches have done on food production and industry. There is no (so far, I mean today, I found none…) research done on GM crops and their environmental impacts, particularly from sustainable P perspective.

Here I plan to use CLCA to evaluate the environmental impact (and economy by using MFA??) by changing traditional crop to AVP1 GM crop. In this study I will compare wild type (WT) and AVP1 transgenic romaine lettuce (*Lactuca sativa* cv. conquistador). This is a study of P fertilizer being applied on romaine lettuce from gate to grave and making a comparison between WT and AVP1 romaine lettuce. The system boundary would be commercial P fertilizers applied on all lettuce in the U.S.

The lettuce includes head lettuce, leaf lettuce, and romaine lettuce. The amount of P fertilizers such as inorganic, organic, and imported, will be identified and quantified. The amount of nitrogen and potassium fertilizers will also be quantified along with P fertilizer. The amount of water will be compared between the two different lettuces as the AVP1 lettuce grows faster and the amount of days of watering would be fewer. Eutrophication will be assessed as well as $N_2O$ emission. As AVP1 lettuce has a bigger root system, I will try to quantify the extra amount of $CO_2$ fixed into the soil via AVP1 lettuce. I will also try to project the impact of AVP1 lettuce on market price. The functional unit of LCA portion is kg usage of N and $P_2O_5$ per ton of lettuce and the functional unit of MFA is kg/ha.

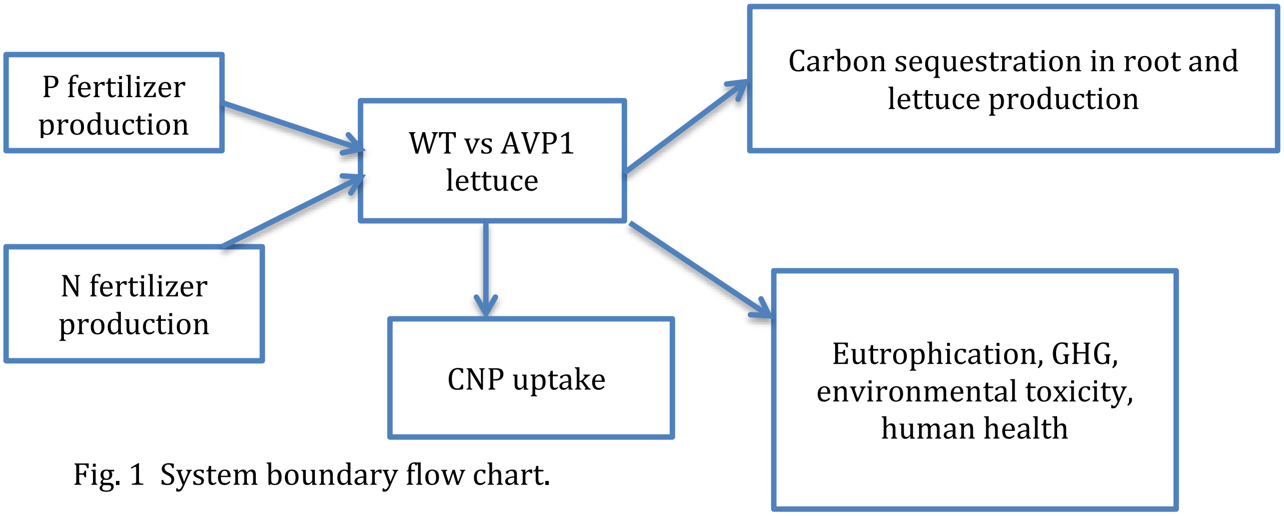

Fig. 1 System boundary flow chart.

## Methodology

*Marketable Yields*

The head lettuce, leaf lettuce, and romaine lettuce are the main focuses for lettuce yields in the U.S. Arizona and California account for 98% of the lettuce production. The data that I collect will only focus on Arizona and California. I assume that all the lands for producing lettuce are arable and have been actively used for agriculture for a long time (Vegetables 2012 Summary). Marketable yields will also be use to calculate carbon sequestration potential.

*Water*

Water budget is calculated by identifying the dripping systems, quantifying the amount of water used in different dripping systems and through evapotranspiration (ET). The usage of different irrigation system for vegetable in California is 21.5% microirrigation, 35.5% sprinkler, and 43% Furrow and flood. I assume that lettuce uses the same proportion in irrigation systems. In 2000, microirrigation shared 20% of total water consumption. Sprinkle and gravity irrigations shared 28% and 52% respectively (Hanson, B.). I have not been able to find the data of the amount of water being used in different irrigation systems in Arizona, so I also assume Arizona uses the same irrigation systems. The AVP1 lettuce would only make a difference by applying microirrigation.

Evapotranspiration is calculated by the following equation:

$ET = Kc \times ET_0$

ET is evapotranspiration, Kc is crop coefficients, and $ET_0$ is the Reference crop ET. I use California Irrigation Management Information System (CIMIS) and The Arizona Meteorological Network (AZMET) to obtain the relevant $ET_0$ for lettuce. The lettuce Kc is collected from FAO Corporate Document Repository (Allen, R.G. et al, 1998).

*Fertilization*

The fertilizer balance is basically calculated by the amount applied to the soil, the amount taken away by lettuce, and the amount washed away by runoff or percolated to groundwater. The last portion will be covered in the section of eutrophication. Soil properties from Arizona and California are very different. Soil P tests from different states are obtained from the database of International Plant Nutrition Institute (IPNI) (Fixen, P.E. et al, 2010). I have not been able to find the amount of P fertilization base upon the soil P test level in Arizona and California. However, Hoque et al. (2010) showed the optimum NPK for growing lettuce in California—N 337 kg/ha and P 225 kg/ha with no K application. Under this fertilization rate, 57.9 tons of iceberg lettuce was yielded and 49 tons of romaine lettuce. I took average of the two as 53.4 tons as an average for all lettuce. I assume that it represent the fertilization amount for California. The data from Arizona I can ask Dr. Roberto Gaxiola in ASU or wait until I finish my lettuce experiments, as I grow different lettuce treatments in the soil from Casa Grande, AZ, with soil test P around 10 ppm. The amount of NPK in romaine lettuce leaf are N 46.2 g/kg, P 6.1 g/kg, and K 49.6 g/kg (Hartz et al, 2007), and I assume this as the data for all lettuce in AZ and CA. I will measure the NPK of my WT and AVP1 lettuce at the end of my experiment. Presumably, AVP1 lettuce would have a higher yield and more P in tissue. This implies that less amount of P fertilizer can be applied to AVP1 lettuce. The differences of dry biomass, leaf area, and marketable yield between WT and AVP1 lettuce can be found in Paez-Valencia et al. (2013). However, the data from Paez-Valencia et al. is base upon N treatment. I can assume P is a little less difference base upon Hoque et al. (2010) if this is necessary. WT and AVP1 P treatment data hopefully are in Dr. Roberto Gaxiola and are being collected.

*Carbon Sequestration*

I hope Roberto has the below ground biomass from WT and AVP1 lettuce in P treatment. AVP1 lettuce should grow a bigger root system (dry root biomass) as well as better marketable yield under 50kgN/ha treatment (Paez-Valencia et al, 2013). I assume that 50kgP/ha would also reach optimal marketable yield. When the lettuce leaf is harvested and the root is left in the soil, the root potentially becomes soil organic matter which enrich the soil and bring the soil C:N:P to a healthier balance. The C:N:P of soil is difficult to quantify as CA and AZ have hundreds of different soil types base upon the soil survey and mapping in USDA data base. The amount of carbon sequestration will be quantified by adding up marketable yield and root biomass.

*Eutrophication*

Stoessel et al. (2012) listed the inventory of average fertilizer emissions: 6% of ammonium nitrate fertilizer is emitted into the air as ammonia, 1.7% as nitric oxide (NO) as well as nitrous oxide ($N_2O$), 35% is leached out as nitrate ($NO_3$) into the soil. P emission into groundwater is 0.07 kg phosphate/ha/yr and P emission into surface water is 0.245 kgP/ha/yr.

*Market*

Days of labor cost can be cut back a week as AVP1 lettuce germinates and grows faster than WT lettuce for about a week (my data). The price of AVP1 lettuce might be cheaper as I will use the lettuce marketable price of 2012 from USDA database (Vegetables 2012 Summary). I use USDA fertilizer database for the price of 2012 to calculate the amount of money saved from using less NPK fertilizer in AVP1 lettuce.

## Result and Discussion

Dry root biomass in AVP1 is more than 2 times higher than WT and has 94% more carbon in AVP1's root than WT's. AVP1 lettuce also has 43 % higher marketable yield than WT. Applying AVP1 lettuce can conserve 78% N and 55% P (**Fig. 1**). It would also reduce 20 kgN/ha/yr emitted as ammonia to the air, 5.7 kgN/ha/yr as NO and $N_2O$, 117kgN/ha/yr as $NO_3$ being leached into the soil, 0.065kgP/ha/yr into groundwater, and 0.23kgP/ha/yr into surface water (**Fig. 3**). The hot spot in pollution is nitrogen. AVP1 lettuce sequesters 7285 kgC/ha while WT sequesters 6388 kgC/ha (**Fig. 2**). This mainly is due to AVP1 lettuce has more robust root system than WT. On the other hand, AVP1 lettuce has lower root N (5387 kg/ha) than WT (6125 kg/ha) (**Fig. 2**). This could be because of AVP1 lettuce's more robust root system can take up nutrient more efficiently than the WT lettuce, AVP1 lettuce does not need to invest as much N in per unit mass of their root for harvesting nutrients. The difference in irrigation will be in dripping system, but I do not have AVP1 lettuce evapotranspiration data as well as water use efficiency data, as I obtained an unexpected result (screw up…) from my experiment in March. **Fig. 4** and **Fig. 5** show the inventories of $P_2O_5$ and N. In $P_2O_5$ inventory, AVP1 lettuce has overall lower impacts. In N inventory, particular attention needed to be paid on $CO_2$-Eq, human toxicity via soil, and terrestrial eutrophication. These are mainly because N fertilizer production is using Haber-Bosch process that requires a lot of energy input. Also, because AVP1 lettuce produces less N pollution (**Fig. 3**) than WT, human toxicity via soil and terrestrial eutrophication have bigger differences between WT and AVP1 lettuce.

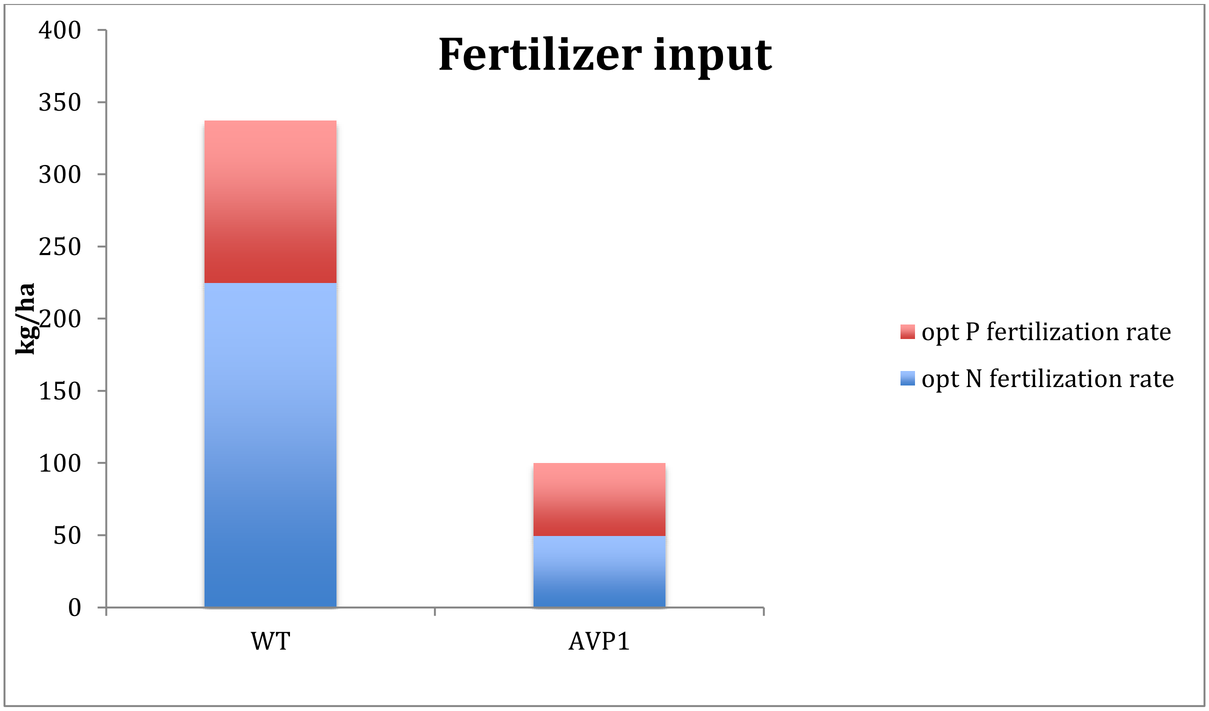

**Fig. 1** Optimum fertilizer inputs in WT versus AVP1 lettuce.

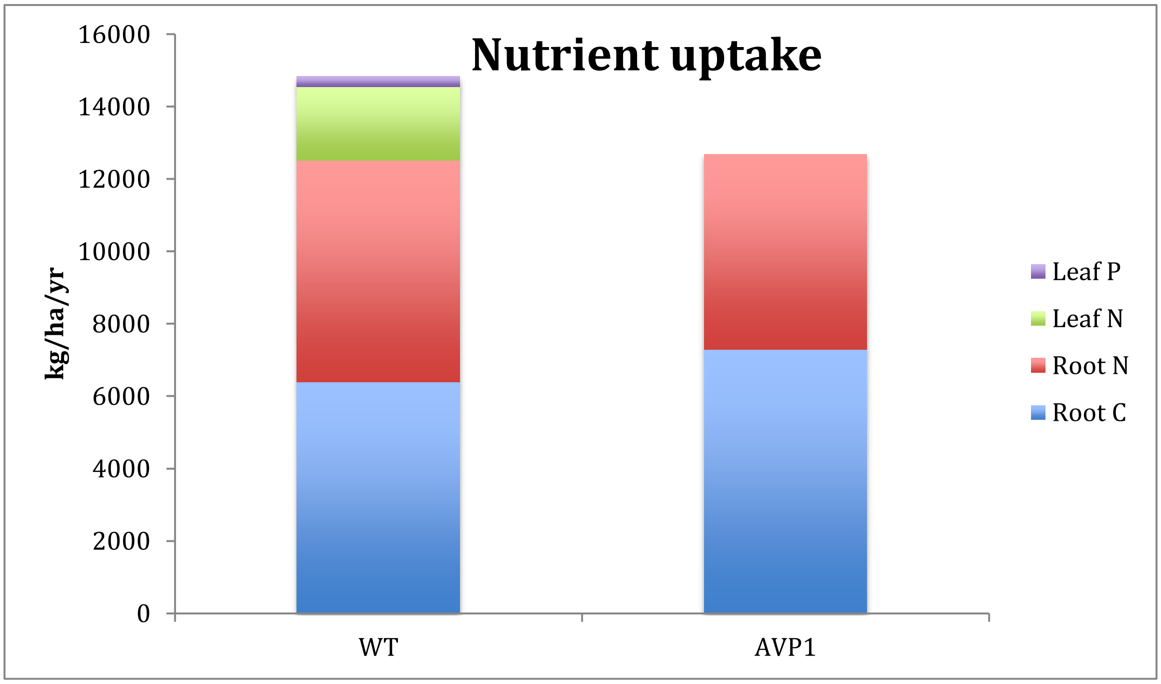

**Fig. 2** Nutrient uptake in WT versus AVP1 lettuce (lack of data on leaf N&P of AVP1 lettuce).

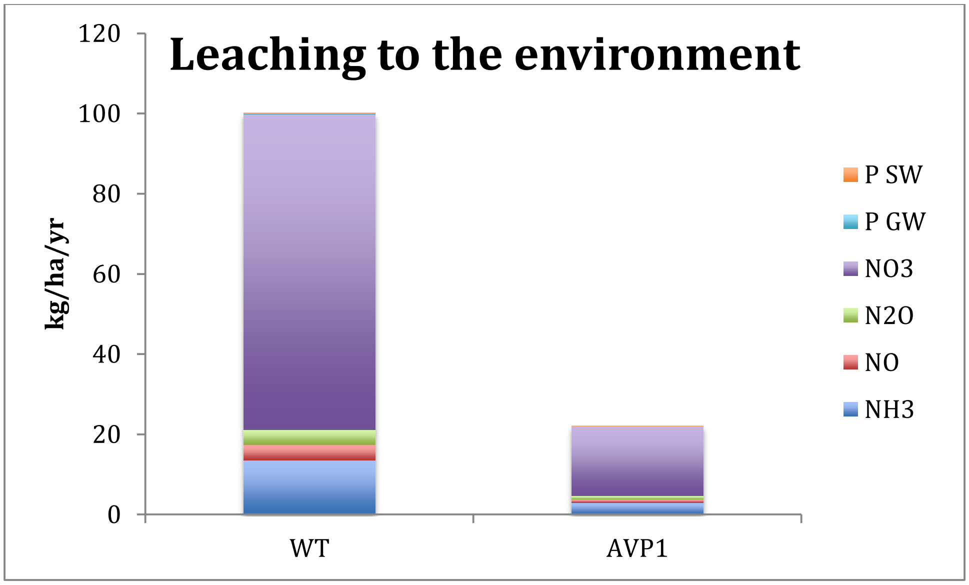

**Fig. 3** Amount of pollution leached out from fertilization. SW: surface water; GW: ground water.

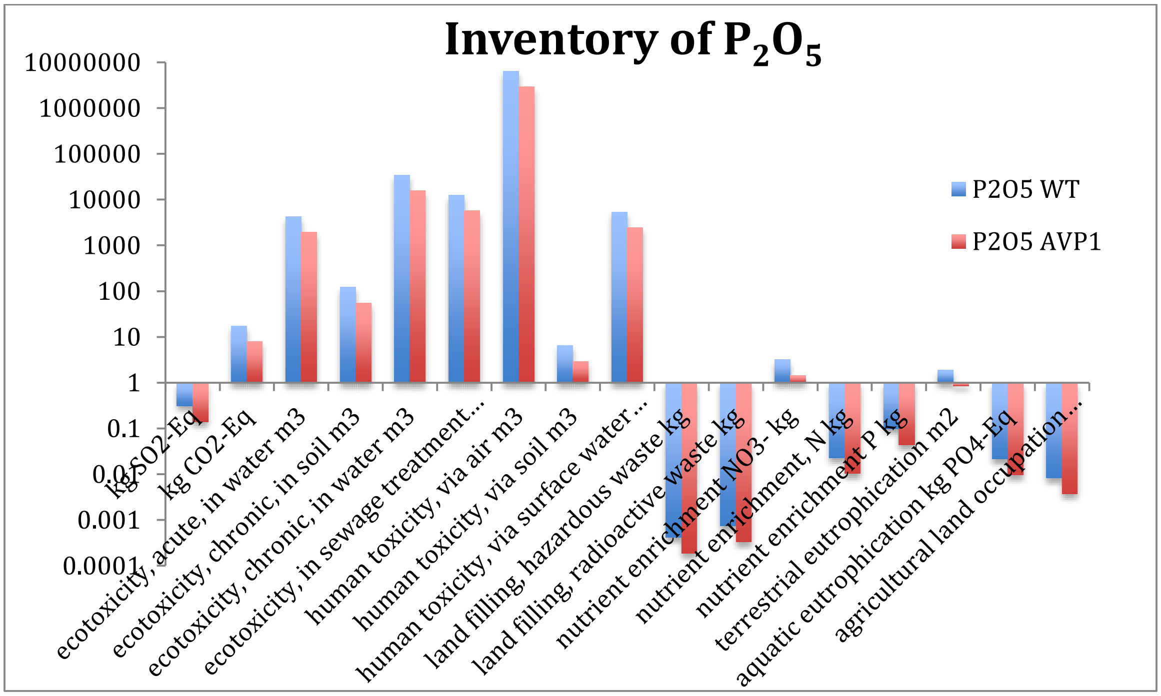

**Fig. 4** The LCA Inventory of using $P_2O_5$ as fertilizer in WT versus AVP1 lettuce.

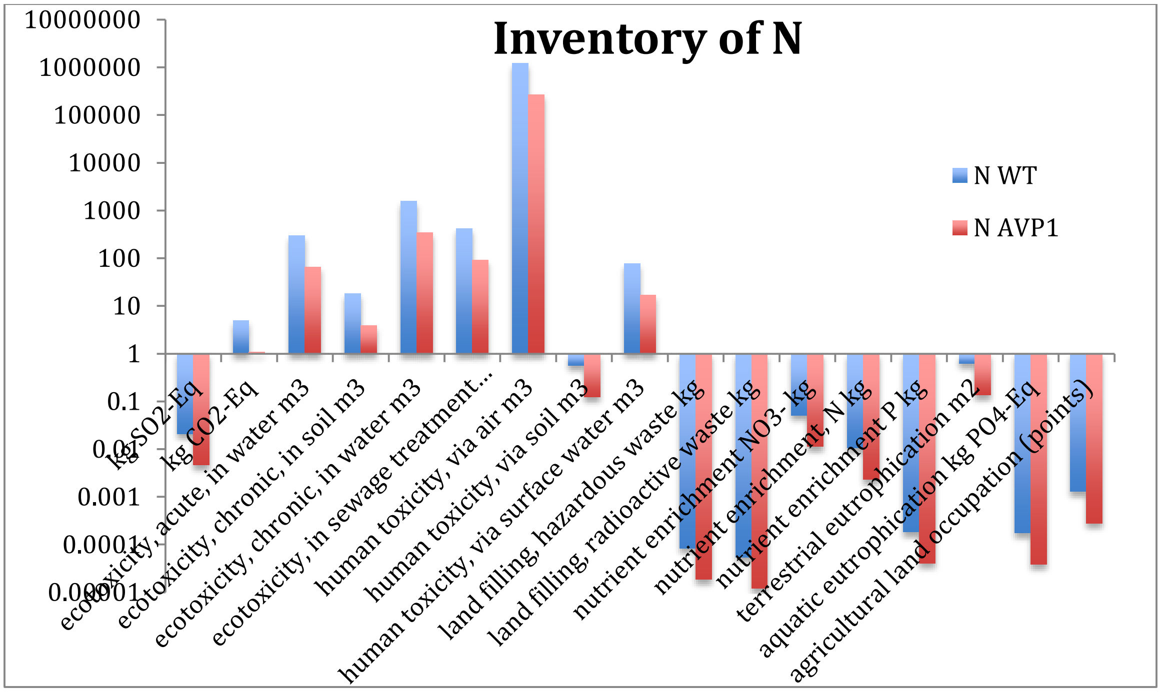

**Fig. 5** The LCA Inventory of using N fertilizer in WT versus AVP1 lettuce.

The biggest uncertainty in this study is in scenario uncertainty, as there are a lot of obstacles in front of getting transgenic crops on the ground. Tremendous efforts and financial support are necessary as well as years to spend on the application processes. In addition, transgenic crops do not have good reputation among public due to various reasons, such as concerns about human health, loss of biodiversity, pesticide and herbicide contamination etc. Lastly, even if the AVP1 crops were able to be on market, how to make it competitive against other big genetic modified crop companies is still a question.

Several parameter uncertainties also need to be addressed. First of all, base upon USGS database, soil property can be very different from county to county. The amount of fertilization rates are heavily based upon how much nutrients are already in the soil. In this study, I only use Hoque et al. (2010)'s study as an optimum N and P fertilization rates. In addition to soil property, soil pH is also an important factor plant nutrient acquisition. Paez-Valencia et al. (2013) conducted the field experiment using Casa Grande soil from Maricopa County, AZ. This soil is an alkaline soil with pH around 8. AVP1 transgenic crops perform best in alkaline soil as their rhizospheres (root zones) have stronger ability in acidifying soil to extract nutrients, especially phosphate. In more acidic or fertile soil such as soils in eastern U.S., AVP1 crops may not perform as good compare to WT. However, most of the soil in western U.S. is alkaline soil and 98% of lettuce is produced in CA and AZ. The uncertainty about soil pH may have less concern as long as this information is used in the U.S. It would be difficult to apply the information from this study in a global setting.

So far the AVP1 gene has only been transferred into romaine lettuce, but not head lettuce and leaf lettuce. I assume that the biological effects of AVP1 gene would be the same in all three kinds of lettuce, but this may not be the case. For example, head lettuce has larger above ground production. It could have higher capacity in carbon sequestration and marketable yield per unit of land.

I made the assumption that AZ uses the same irrigation systems as CA. This assumption has been made due to limited data that I found. I need to talk to more experts in this area to obtain relevant information. In CA, there is only 21.5% of irrigation systems is dripping irrigation. The optimum scenario of applying AVP1 lettuce is combining dripping system and reducing fertilization rate in a alkaline soil.

The Eutrophication data are obtained from Stoessel et al. (2012) and that is a tertiary data. Also, those data were collected in Europe base upon its citations. It has high uncertainty to apply it in a U.S. system boundary, but that is the only data I can obtain from the Ecoinvent about lettuce (**Table 1**).

**Table 1** Data Quality Assessment table (1= Good, 5= Bad).

| Criteria | Score |
|---|---|
| Impact on Final Result | 3 |
| Acquisition Method | 2 |
| Independence of Datta Supplier | 2 |
| Representation | 3 |
| Temporal Correlation | 4 |
| Geographical Correlation | 5 |
| Technological Correlation | 1 |
| Range of Variation | 2 |

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