
**Well nodulated** soybean roots.

# Soybeans and Biological Nitrogen Fixation: A review

By Ignacio A. Ciampitti and Fernando Salvagiotti

Soybean crops provide one of the world's most important sources of protein and oil. Historically, soybean yield improvements have occurred from biomass gains and increased partitioning to the seed, which all require large amounts of N (Balboa et al., 2018) supplied by BNF and/or the soil. In soybean, the contribution of N from BNF ranges from 0 to 98% depending on many factors, the most important being rhizobial activity. A past review on BNF documented an average contribution of 50 to 60% (Salvagiotti et al., 2008). Recent values recorded in Argentina (60%; Collino et al., 2015) fall within this range, but values of up to 80% have been noted in less fertile soils in Brazil (Alves et al., 2003).

The main question motivating this review is whether BNF can supply sufficient N for high-yielding soybean systems (>7 t/ha) while maintaining a neutral partial N balance. Our data comprised 733 observations from 60 studies conducted from 1955 until 2017, including data on seed yield (adjusted to 13% moisture), BNF, and plant N uptake. A partial N balance was calculated as:

Partial N balance = fixed N in aboveground biomass – N in harvested seeds.

A negative partial N balance indicates that the amount of N exported in seeds is larger than N fixed, and thus a net "soil N depletion" occurs, which may affect the system N balance.

## Seed Yield, Plant N Uptake, and $N_2$ Fixation

The overall mean seed yield was 3.1 t/ha, and the maximum value was 8.3 t/ha (**Figure 1**). Plant N uptake averaged 245 kg N/ha, with a maximum N uptake close to 560 kg N/ha. The slope of the middle regression line indicated that, on average, 81 kg plant N was required for every 1 t of soybean produced. However, **Figure 1** shows a four-fold

**SUMMARY**

A review of 60 studies reporting on biological N fixation (BNF) in soybean was done to study the limits to which BNF can satisfy plant N demand. This review confirmed that BNF could satisfy plant N demand up to 200 kg N/ha. The N-gap (plant N uptake minus fixed N) widened rapidly if plant N demand exceeded 370 kg N/ha, which suggested the need for additional N under conditions of high yield potential. The partial N balance (fixed N minus N removed in seeds) was negative on average but approached neutral or positive values when BNF contributed at least 58% of plant N uptake.

**KEYWORDS:**
biological fixation; partial balance; nitrogen gap; soybean credit; high yields.

**ABBREVIATIONS AND NOTES:**
N = nitrogen; BNF = biological nitrogen fixation.

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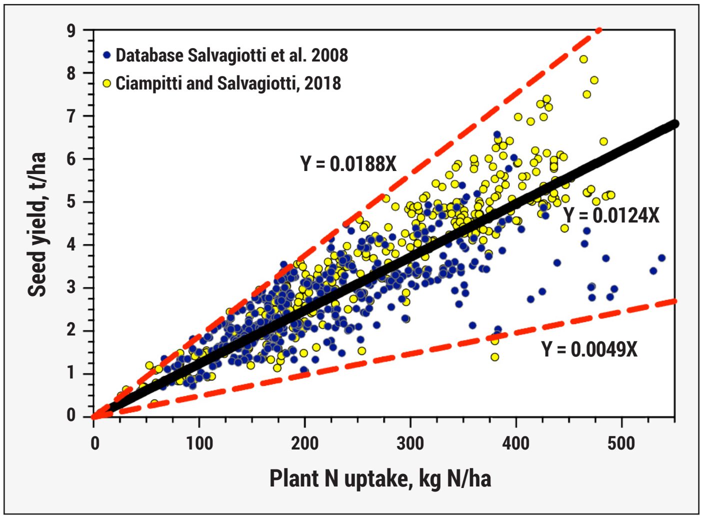



**Figure 1. Soybean seed yield versus plant N uptake in studies conducted from 1955 to 2017. Blue circles correspond to the database collected in the previous review paper from Salvagiotti et al. (2008), and the yellow circles refer to the new database gathered by Ciampitti and Salvagiotti (2018).**

variation in the N requirement per t of yield produced—from maximum N dilution (upper boundary line) close to 53 kg N/t to maximum N accumulation (lower boundary line) of 204 kg N/t.

Overall mean $N_2$ fixation was 137 kg N/ha, and the maximum value was 372 kg N/ha (**Figure 2**). The relative contribution of $N_2$ fixation to plant N uptake (BNF%) was 56%, with 50% of the data concentrated between 44 to 72%.

Seed yield and $N_2$ fixation were linearly related to BNF% (**Figure 2**). For the low BNF% group (green circles; less than 44% BNF), lower yield was associated with low BNF%. This group represents soybean systems more dependent on soil (or fertilizer) N in order to satisfy plant N demand. The high BNF% group (blue circles; above 72% BNF) fixed 59 kg N/t yield, or about twice the amount compared to the low BNF% group, while still showing a maximum yield above 7 t/ha and $N_2$ fixation above 300 kg N/ha.

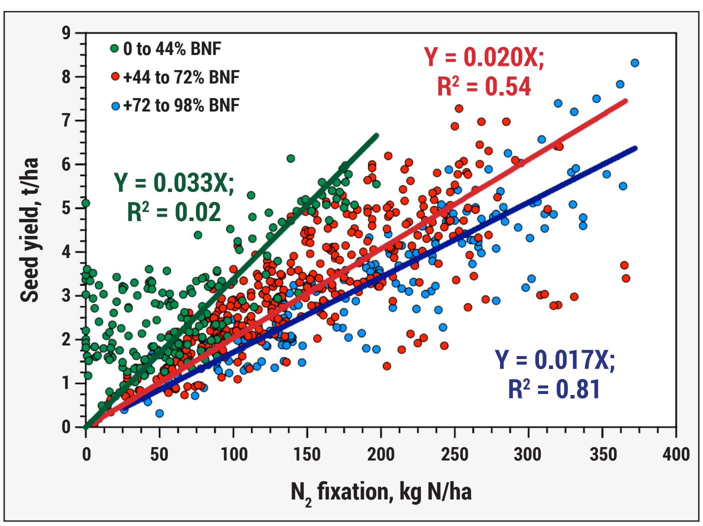



**Figure 2. Soybean seed yield versus plant $N_2$ fixation in studies conducted from 1955 to 2017. Green circles referred to data points with a BNF contribution to plant N uptake (BNF%) ranging from 0 to 44%, red circles from 44 to 72%, and blue circles above 72%.**

## $N_2$ Fixation and Plant N Demand: The "N-gap"

This study of the relationship between $N_2$ fixation and plant N uptake was used to quantify the so-called "N-gap", which is understood to be the soybean N demand not supplied by BNF. Overall, median $N_2$ fixation represented by the 50% quantile line in **Figure 3** shows a N-gap that increases linearly as plant N demand rises. Maximum BNF capacity is displayed as the frontier (99%) quantile line, which represents the maximum $N_2$ fixation achieved at each plant N uptake level. This quadratic model reflects that the maximum BNF capacity to supply N to soybeans decreases more than proportionally as plant N demand increases. Reasonable synchrony between N supply and demand is achieved until 200 kg N/ha, with the N-gap for the maximum values for the plant N uptake-$N_2$ fixation relationship increasing at a similar rate until 370 kg N/ha, after which the N-gap becomes quite large. For example, when plant N uptake was 330 kg N/ha the N-gap was 38 kg N/ha, but it went up to 60 kg N/ha as plant N uptake reached 400 kg N/ha (**Figure 3**). These results suggest that a larger plant N uptake may tap into N sources other than BNF in high-yielding environments.

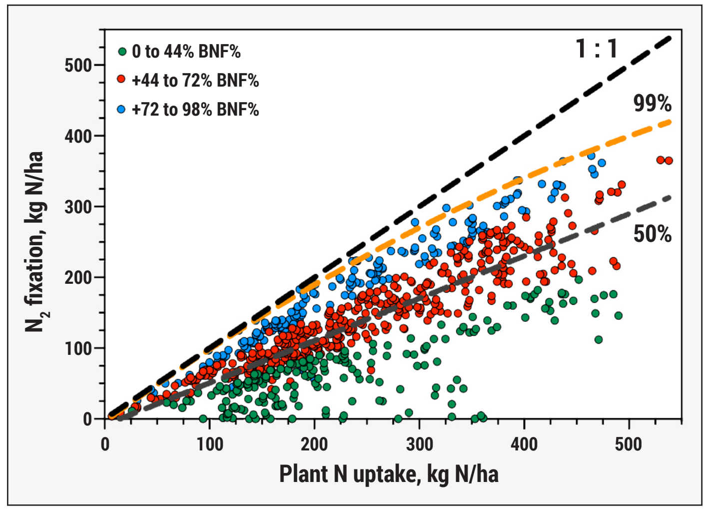



**Figure 3. Relationship between the contribution of $N_2$ fixation and plant N uptake in soybeans, N-gap expressed as the plant N uptake minus fixed N, for BNF% groups ranging from 0 to 44%, red circles for BNF% from 44 to 72%, and blue circles for BNF% above 72%.**

## Partial N Balance and the Soybean "N-credit"

The partial N balance (excluding BNF contribution from roots) presented an overall mean of -47 kg N/ha, with 50% of the data points concentrated between -75 to -11 kg N/ha. The partial N balance for the low BNF% group averaged -100 kg N/ha, with an overall yield of 2.9 t/ha, and $N_2$ fixation of 62.5 kg N/ha. The high BNF% group had an average partial N balance of -3.4 kg N/ha, with an overall yield of 3.6 t/ha, and $N_2$ fixation of 202 kg N/ha.

Cumulative frequencies for the partial N balances (**Figure 4**) indicate that only 3% of the data (n = 4) had positive balances for the low BNF% group, while oppositely, for the high BNF% group, 40% of the data had positive balances (n = 41).

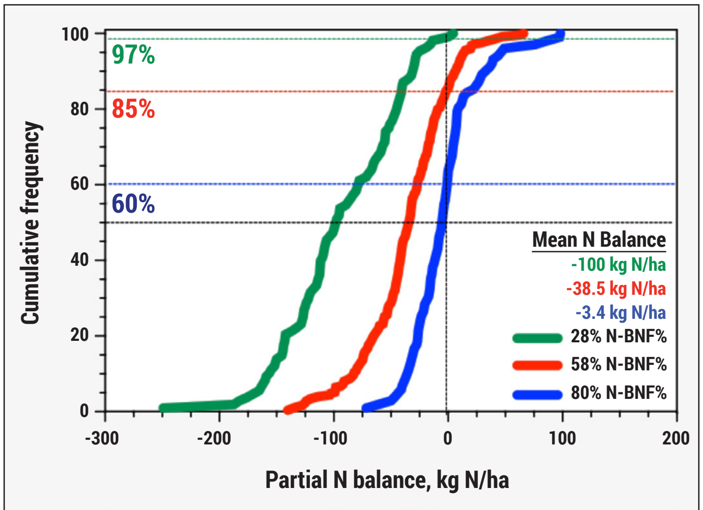



**Figure 4. Cumulative distribution for partial N balance in soybean systems. Green, red, and blue lines depict the 0 to 44%, 44 to 72%, and 72 to 98% BNF groups, respectively.**

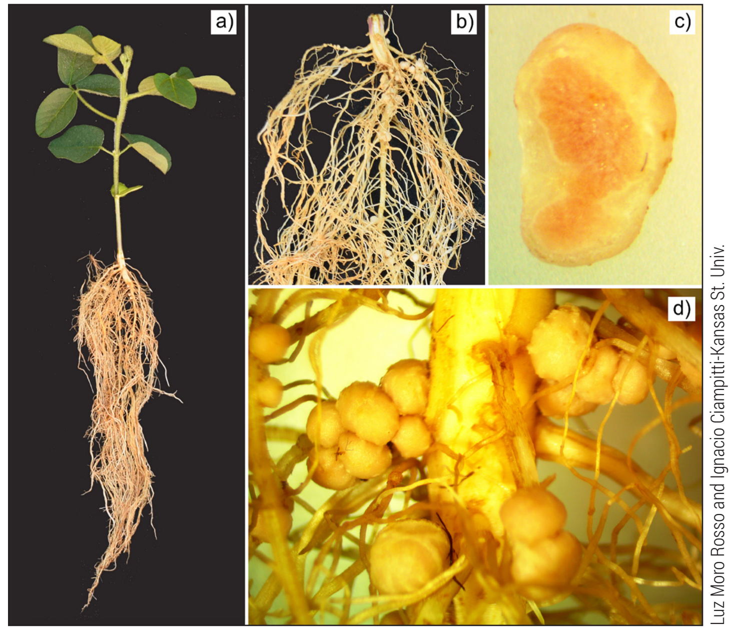
In the future, partial N balance calculations should account for potential N loss via leaf drop and the contribution of roots, as well as a retrieval of in-field N rhizodeposition from thinner roots. It is evident that after considering this current review, more efforts should be focused on collecting data concerning the contribution of roots to obtain a more precise quantification of BNF impact on the partial N balance.

Lastly, the soybean N-credit or "soybean rotation effect", commonly used to make N-fertilizer recommendations in U.S. maize-soybean systems, is entirely dependent on soil N mineralization of soybean residues with low C:N ratios (Bundy et al., 1993; Gentry et al, 2001; 2013). From this review, it seems likely that there can be a net gain in the partial N balance from BNF, but it likely occurs with more frequency when BNF is above 70%, exceeding the N removal from soybean seed harvest. However, it is also likely that there is no soybean N-credit when BNF is below 42%.

## Conclusion

The overall contribution of BNF in soybean systems is between 50 to 60% with maximum BNF satisfying plant N demand until 200 kg N/ha. The N-gap (plant N uptake minus fixed N) widens after 370 kg N/ha, which suggests a need for additional N due to high crop yield potential. Partial N balances, excluding root N contribution, showed negative values across varying levels of BNF, but they become closer to neutral as BNF contribution increased above 70% relative to the plant N uptake.

> **TAKE IT TO THE FIELD**
>
> The quantity of BNF from low and medium BNF% groups (<72%) should not be relied upon as a N credit in a maize-soybean cropping rotation.




**Soybean plant at V3 (three-leaf) stage** growing without inorganic N supply under greenhouse conditions. The seed was inoculated with an inoculant containing Bradyrhizobium japonicum strain. b) and d) show roots (and nodules). c) shows the nodule starting its activity, based on its internal coloration.

Future BNF improvements should attempt to identify highly efficient *Rhizobium* strains adapted to environments with high plant N demand and/or reducing the negative impact of soil nitrate concentration on BNF. The priority for research is to improve the understanding of the contribution of roots, the impact of N mineralization, and the plant N processes that have the biggest effects on BNF in high-yielding soybean systems (>7 t/ha) around the world. **BC**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