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Nitrogen credits after peanut (*Arachis hypogaea* L.)

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Abstract

State-level cooperative extension services provide fertilizer recommendations for row crops in the United States. Of these, nitrogen (N) recommendations are arguably the most important because N is the most common yield-limiting nutrient in nonlegume crop production systems. Throughout the peanut (*Arachis hypogaea* L.) growing region of the United States, Cooperative Extension Services generally recommends 22–67 kg N/ha credit to crops following peanut, likely due to the assumption that peanut, being a legume, contributes N to the following crop. The body of peer-reviewed literature indicates that N credits from peanut to the subsequent crop are negligible. Recent literature indicates that apparent differences in yield following peanut compared to a nonlegume are a result of nonlegume crop residue favoring N immobilization rather than N mineralization from peanut residue. Taken together, recent research corroborates the few previous scientific publications addressing the issue, namely, that cooperative extension service recommendations to reduce N fertilization to crops after peanut are not supported by the peer-reviewed literature. Future field research should include summer fallows to determine if yield differences between legumes and nonlegumes are due to N credits by the legume or N immobilization by nonlegumes. Data on N loss pathways following peanut are needed to identify management strategies that can mitigate N losses after peanut harvest. In conclusion, the preponderance of peer-reviewed science does not support current Extension recommendations regarding peanut N credits to the following crop.

1 | EXTENSION RECOMMENDATIONS

Crops that follow peanut (*Arachis hypogaea* L.) are often observed to have improved growth and yield compared to crops grown after nonlegumes. These observations have been attributed to improved soil nitrogen (N) availability after peanut. Crops grown after peanut are thought to access this increased soil-N pool, attributed as a peanut N credit to the subsequent crop (Anuar et al., 1995; Ding et al., 1998; Hilton, 2018; Meso et al., 2007). Although there are other definitions for "N credits" (see Section 3), in this paper, "N credits" refer to a common understanding as the N fertilizer replacement value of a legume to a subsequent crop.

Throughout the peanut-growing region of the southeastern United States, N credits after peanut are commonly recommended by Cooperative Extension Services. In Georgia, the state with the largest peanut-production acreage in the United States, Extension recommends reducing N fertilization to winter wheat (*Triticum aestivum* L.) following peanut by 22–45 kg N/ha (20–40 lb N/ac) (Harris, 2013). However, there is consensus among soil scientists in the region that soils of the Southeast do not hold N for long periods because of sandy textures, frequent leaching rainfall events, and the warm climate (Breitenbeck, 1990; Pettiet, 1990). These combined factors are thought to be responsible for the rapid mineralization of soil organic N and loss from the rooting zone in this region. This is the rationale behind why Southeastern soil test laboratories do not issue preplant soil N tests, such as the Illinois soil nitrogen test. Nor do they recommend N credits based on preplant soil organic matter, which are applicable to the northern part of the United States (though this is an area with plenty of research opportunity) (Wall et al., 2010; Williams et al., 2007).

Somewhat surprisingly, N credit recommendations do not vary much between the northernmost and southernmost peanut-producing states. Virginia recommends up to 50 kg N/ha (45 lb N/ac) (Maguire & Heckendorn, 2011, 2023), while Oklahoma estimates a 22–97 kg N/ha (20–60 lb N/ac) credit after "plowing down" postharvest peanut or soybean (*Glycine max* (L.) Merr.) residue. South Carolina recommends reducing N application to cotton (*Gossypium hirsutum* L.) by 22–34 kg N/ha (20–30 lb N/ac) following peanut (Jones et al., 2011), while Alabama recommends reducing N application to wheat by 22 kg N/ha (20 lb N/ac) after peanut (Mitchell et al., 2012). Similarly, Alabama recommends a 22 kg N/ha (20 kg N/ac) credit to canola (*Brassica napus* L.) after peanut. Interestingly, Texas, the state with the second largest peanut-production acreage in the United States, makes no such claims about N credits from peanut to the subsequent crop.

If the Virginia N credit is substantiated, a 50 kg N/ha (45 lb N/ac) reduction over Virginia peanut acreage (Maguire & Heckendorn, 2011, 2023) would reduce N loading to the environment by nearly 500,000 kg N (1.1 million lb N) and save growers approximately \$200,000 (assuming \$0.88/kg N or \$0.40/lb N) in that state alone each year (USDA NASS, 2019), assuming a peanut–nonlegume rotation. Georgia could reduce N applications by approximately 6–12 million kg N (13–26 million lb N), saving \$5.3–10.6 million, per year if their N credit recommendations were followed (Harris, 2013). On the other hand, if N credit recommendations are applied but not substantiated, yield losses of the subsequent crop could occur throughout the peanut-growing region of the United States. Thus, the accuracy of peanut N credits to the subsequent crop would have large agronomic, economic, and environmental consequences.

There is evidence that recommendations regarding peanut N credits are changing. A 2011 Florida Extension publication that recommended a N credit of 34 kg N/ha (30 lb N/ac) after growing peanut (Wright et al., 2011) was recently updated to omit any specific reference to peanut N credits (Wright et al., 2018). Notably, the publication continued to reference N credits provided by other leguminous crops. Similarly, an Alabama recommendation of 22–34 kg N/ha (20–30 lb N/ac) credit to cotton (Mitchell & Phillips, 2010) was updated to remove any mention of N credits to cotton following peanut, although a 22 kg N/ha (20 lb N/ac) credit continues to be applied to canola (Mitchell & Huluka, 2012).

Core Ideas

- Nitrogen (N) credits from peanut to the subsequent crop are negligible.
- Data on N loss pathways following peanut are needed to identify management strategies that can mitigate N losses after peanut harvest.
- Peer-reviewed science does not support current Extension recommendations regarding peanut N credits to the following crop.

2 | RESIDUE LOAD AND HAY REMOVAL EFFECTS ON PEANUT N CREDITS

Nitrogen credits should depend on the amount of residual biomass, since more biomass means more total N applied to the soil. In Virginia, N credits are adjusted for stand and the amount of biomass produced for some legumes (soybean, alfalfa [*Medicago* L.], and clover [*Trifolium spp.*]), yet they do not make an adjustment for peanut (Maguire & Heckendorn, 2011, 2023). For example, the Virginia soybean N credit to subsequent crops is 0.0093 kg N/kg grain (0.5 lb N/bu). Soybean with a high yield (which they define as >2000 kg/ha or >30 bu/ac) is allotted the full 100% N credit to a subsequent crop. A low soybean yield (<1700 kg/ha or <25 bu/ac) only receives a 50% N credit to the subsequent crop (i.e., 0.0047 kg N/kg grain or 0.25 lb N/bu). Similar recommendations are made for alfalfa and red clover (*Trifolium pratense* L.). Conceptually, this makes sense for soybean since the soybean harvest index is relatively stable (Spaeth et al., 1984). However, no "yield allowance" is made for peanut, perhaps because digging losses are highly variable (Lamb et al., 2004) such that yield and biomass are not well correlated for peanut.

Oklahoma recommends that when peanut (and other legume) residues are removed as hay, negligible N credits to the following crop are expected (Caddel et al., 2006). However, evidence contrary to this recommendation was provided by Balkcom et al. (2007), who investigated the contribution from peanut residues on subsequent rye (*Secale cereale*) biomass production and found that biomass yields were similar regardless of peanut hay removal or retention on a Dothan sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). A similar experiment also found no differences between peanut residue retention or removal on seed cotton yield, N uptake, or leaf N concentration (Meso et al., 2007). These authors concluded that aboveground peanut residue does not provide substantial amounts of N to a subsequent cotton crop. Although one should be cautious about drawing general conclusions from two studies, these experiments agree on the question regarding contributions of aboveground peanut residue (i.e., hay) N to the subsequent crop: it does not. These studies imply that baling and removing peanut hay does not impact N credits to a subsequent winter or summer crop. It would be natural to think that if hay is removed, N credits should be reduced.

Indeed, most states that recommend a N credit after peanut do not consider whether residues are removed for use as hay or left in the field. Most of the peer-reviewed literature agrees that the removal of peanut residue does not affect N uptake or yield of the following crop in the Southeast United States (Balkcom et al., 2004, 2007; Jani, Mulvaney, Balkcom, et al., 2020; Meso et al., 2007). Research outside the United States provides evidence to corroborate these findings. Studies conducted in northeast Thailand used labeled ^{15}N peanut residues as the only added N source for subsequent corn (*Zea mays* L.) production and found that only 16.4–27.5 kg N/ha (14.6–24.5 lb N/ac) were contributed from peanut residue to corn (McDonagh et al., 1993). Given that N use efficiencies increase as applied N rates decrease, this is a remarkably low N contribution from peanut to a crop with large N requirements. The same study found that corn yield increased by only 1% (20 kg/ha) following nodulating peanut compared to a fallow control (peanut hay was removed), and corn yield decreased by 10% (188 kg/ha) when following non-nodulating peanut. Unfortunately, statistics were limited to standard errors of means and the study was conducted over 1 site-year. However, these results highlight a couple of interesting points: (1) Peanut N fixation, compared to non-nodulating peanut, compensated for a decrease in corn yield, and (2) the contribution of nodulating peanut to corn yield was not substantial (only 1%) compared to a fallow control. Although one should hesitate to attach weight to a study without rigorous statistics conducted over 1 site-year, the results agree with the majority of peer-reviewed literature and highlight the relative importance of peanut nodulation compared to a fallow control. A similar study using ^{15}N-labeled peanut residue in rice (*Oryza sativa* L.) found that 11–19 kg N/ha (10–17 lb N/ac) was contributed to rice, but peanut residue was dried, stored for at least 2.5 months between peanut harvest and rice planting, and deployed during land preparation for rice (Toomsan et al., 1995). This methodology would be expected to substantially increase N contributions to subsequent rice, yet the peanut residue only contributed 11–19 kg N/ha (10–17 lb N/ac). Regardless of methodology, peanut N contributions to rice were notably small and agree with the majority of peer-reviewed literature. A field study conducted in Ghana, where peanut hay was removed, found that no peanut N credits were available to corn; indeed, results indicated negative N credits to corn were associated with early peanut and soybean cultivars (Ennin et al., 2004). While these authors concluded that maturity group of legumes, presumably a proxy for duration of growth and N accumulation, was the determining factor for N credits to the subsequent crop, they found that peanut did not supply N to corn regardless of maturity.

Several litterbag studies, in which residue is loaded into mesh bags and retrieved periodically from the field to estimate residue decomposition and nutrient mineralization rates, have shown small potential N credits to a subsequent crop. The nature of litterbag studies demonstrates *potential* N credits because N mineralized from residues may or may not be available to a subsequent crop. It is also recognized that litterbags underestimate decomposition rates (Bradford et al., 2002; Dornbush et al., 2002) such that mineralization in a field setting is likely faster than litterbags would indicate. With that in mind, Jani et al. (2019) conducted a residue litterbag study on sandy soils in Florida using various peanut residue loads representative of different parts of a windrow, since the outside of a windrow contains less residue than the center of the windrow. Predictably, less N (on a mass per area basis) was mineralized from small residue loads (windrow edges) and more N was mineralized from large residue loads (windrow centers). For example, using fall tillage at the low residue rate of 1.1 Mg residue/ha (0.5 US tons/ac), the amount of potential N mineralized during the wheat season was predicted to be 3 kg N/ha (3 lb N/ac), but under the highest residue load (6.7 Mg/ha or 3.0 US tons/ac), the potential N mineralized increased to 35 kg N/ha (31 lb N/ac). During a subsequent cotton season, those potential N credits were reduced to 2 and 5 kg N/ha (2 and 4 lb N/ac), respectively. The only treatment showing potential N credits approximating those recommended by the University of Florida Cooperative Extension Service was when residue was applied at the highest rates representing the center of windrows. That said, it could be that leaf drop after windrowing may contribute more N in the center of the windrow, since an accumulation of N-rich leaves may increase N contributions. A laboratory incubation study showed that dried and ground peanut leaves applied at a rate of 3.9 Mg/ha (3500 lb/ac) mineralized 25 kg N/ha (22 lb N/ac) over 252 days at 25°C (Jani, Mulvaney, Balkcom, et al., 2020). Given the fact that these residues were applied at high leaf litter rates, ground to pass a 1-mm sieve, and incubated at high temperatures, this likely represents an upper range of N that may be provided from peanut leaves. The same study included peanut stems and a 1:1 mixture of leaves:stems, but found that only leaves increased N mineralization compared to a soil-only control. The authors concluded that peanut residues are expected to contribute minimal N to the following crop, and even the N contribution from leaves would likely not be sufficient to explain the "windrow effect" sometimes observed after peanut production. However, the center of windrows typically contain substantially more total biomass than was applied in this laboratory study (Jani, Mulvaney, Balkcom, et al., 2020), so it is possible that N contributions from large amounts of biomass in windrow centers may contribute more N to the subsequent crop simply by loading more residue N into the system in windrow middles. Peanut residue that is windrowed behind the peanut combine does increase potential N availability in the middle of the windrow compared to between windrows (Jani et al., 2019), which might explain the windrow effect. Additionally, research indicates that if spreaders are used to evenly distribute residue, the total potential N credits would not change since residue load does not alter the decomposition rate (on a basis of percent of initial residue N applied). Naturally, more biomass means more total N applied, but residue will decompose at the same rate regardless of residue load, according to Jani et al. (2019). It remains unclear if the windrow effect is due solely to increased N mineralization within the windrow, or if it is due to increased soil organic matter (with related effects on infiltration, soil water- and nutrient-holding capacity, microbial community dynamics, etc.), or possibly if the residue protects seedlings from physical damage, such as wind scouring or cold damage. It seems likely that the windrow effect is the cumulative result of all these factors, but there is no research to verify or refute this.

While the importance of residue loads (or using peanut yield as a proxy) is generally not acknowledged in Extension literature (the exceptions being Oklahoma [Caddel et al., 2006] and Florida [Jani & Mulvaney, 2019]), evidence supports the concept that residue loads (i.e., yield) are likely to affect potential N credits to a subsequent crop (Jani et al., 2019). However, additional N credits from increased residue load assume that N availability will be synchronized to the demand of the subsequent crop. Virginia makes the notation that N credits only apply to peanut vines (Maguire & Heckendorn, 2011, 2023), which implies the N credit should not be applied if residue is baled and removed from the field, although they do not specifically state such. No other state mentions the removal of peanut hay in relation to N credits.

3 | PEANUT ROTATION EFFECT

The consensus of research conducted in the field, laboratory, and using litterbags is that peanut residue does not supply significant quantities of N to a subsequent crop to justify a N credit, but these studies do not answer the following questions: Does growing peanut itself contribute N to a subsequent crop? Is there a "rotation effect," whereby peanut increases yield (or decreases the requirement for mineral N) of the subsequent crop? Many field trials that attempt to address these questions do not include a summer fallow control in the treatment structure to enable accurate estimation of peanut N credits to a following crop (for examples in peanut, see Hilton (2018), or soybean, see Ding et al. (1998) and Bundy et al. (1993)). Without a summer fallow in the treatment structure, one cannot distinguish between N mineralization from legumes and N immobilization by nonlegumes. This results in potentially erroneous conclusions that greater yield responses after a legume are due to N mineralization and not reduced yields (due to N immobilization) after a nonlegume.

It is common to assume that differences in crop yield response after peanut are due to N contributions from peanut. Indeed, the published definition of "N credit" is the N fertilizer rate required to provide a rotational corn–corn yield equal to that of a soybean-corn yield (Gentry et al., 2001; Lory et al., 1995; Morris et al., 2018). While this definition for determining fertilizer replacement value is useful, it has resulted in a fundamental misunderstanding of the role of legumes in N contributions by assuming that N immobilization of the nonlegume in rotation plays no role in subsequent crop response to mineral N. That is, it is possible that the legume does not supply N as much as the nonlegume immobilizes N, such that additional N fertilization is needed after a nonlegume, not the other way around. It may be the case that mineral N is immobilized by carbonaceous residues rather than N contributed from leguminous residues, particularly in the humid Southeast United States where N mineralization is rapid (Mulvaney et al., 2017). There are only a few methods available to quantitatively determine N contributions to the subsequent crop in a field setting: (1) using ^{15}N isotope studies, (2) inclusion of a non-nodulating legume in the experimental design, and (3) use of a fallow control in comparison with the legume. Naturally, each of these methods has advantages and disadvantages, but it is beyond the scope of this paper to discuss them here. It is sufficient to say that without these methods, or some combination thereof, one cannot distinguish between a N credit from legumes and N immobilization from nonlegumes.

Research in North Carolina showed no effect of peanut on cotton or corn yield when grown in various rotations under both conventional and reduced tillage (Jordan et al., 2008). Research conducted in Florida over 4 site-years used peanut, cotton, and a summer fallow control to determine fertilizer replacement values to a subsequent winter wheat crop (Jani, Mulvaney, Erickson, et al., 2020). Winter wheat grain yield after peanut, cotton, or summer fallow was not affected in three of 4 site-years. While winter wheat grain yield after cotton was lower in the remaining site-year of that study, grain yield after peanut was never greater than the yield following the summer fallow control (Figure 1). Furthermore, recent research showed that carinata (*Brassica carinata* A. Braun) planted after peanut produced similar yield to that

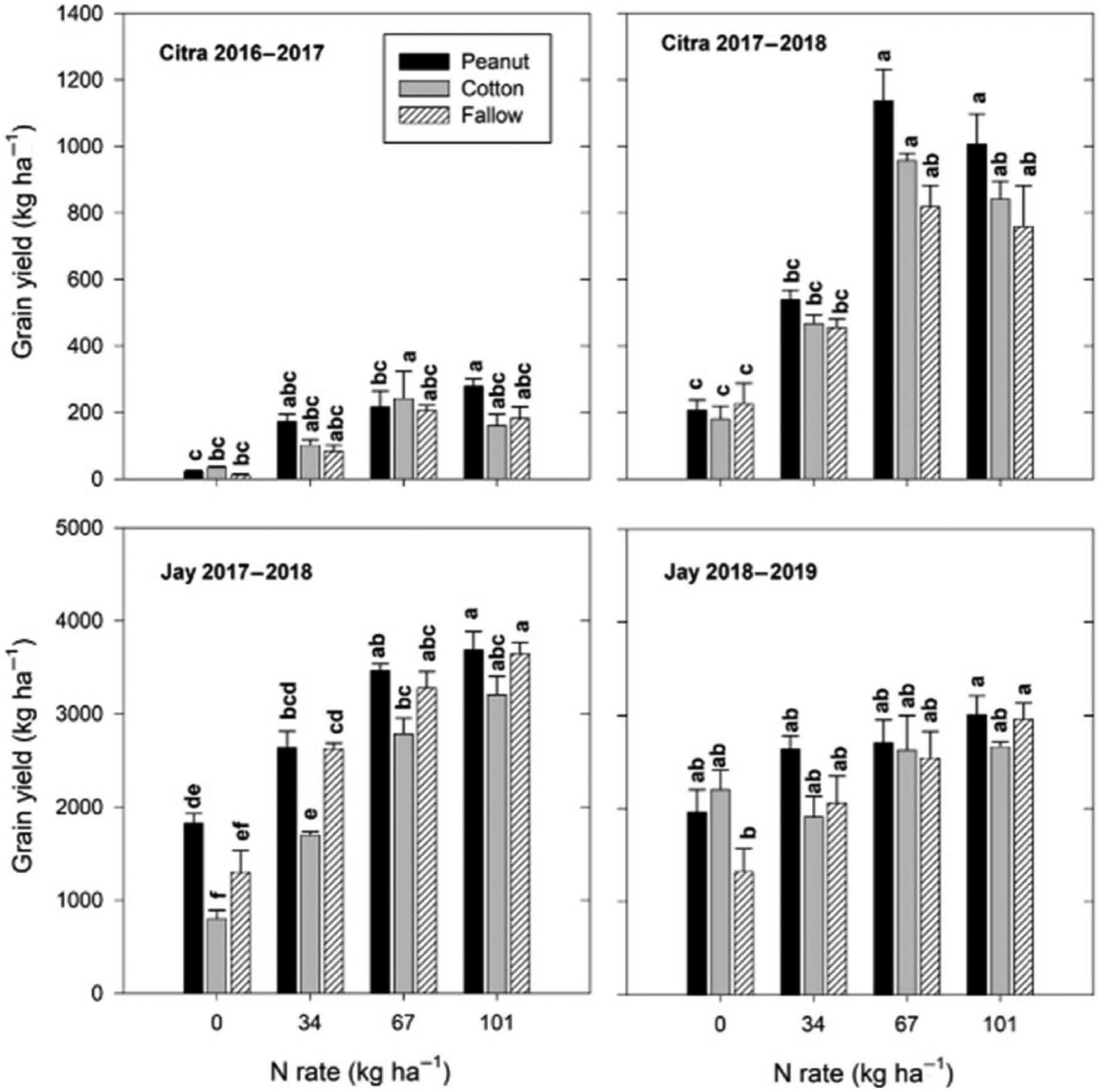

FIGURE 1 Winter wheat (*Triticum aestivum* L.) yield under four nitrogen rates grown in rotation after peanut (*Arachis hypogaea* L.), cotton (*Gossypium hirsutum* L.), and summer fallow in Florida. During three of the 4 site-years, wheat yield was not different regardless of previous crop history. Although wheat yield after peanut was never different than the fallow control, it was lower after cotton during 1 site-year (Jay 2017–2018) at low nitrogen rates, providing evidence of nitrogen immobilization by cotton residue rather than nitrogen credits from peanut residue. Within site-year, different letters signify different means at $p < 0.05$. Data adapted from Jani, Mulvaney, Erickson et al. (2020).

planted after summer fallow based on 4 site-years of field data (Bashyal et al., 2023). These studies provide evidence that, while previous crop history does not always affect N dynamics of subsequent winter crops in the Southeast United States, cotton residue can immobilize soil N, while peanut residue does not significantly increase N availability (Iboyi et al., 2023; Jani, Mulvaney, Erickson, et al., 2020). Indeed, Georgia Extension recommends increasing N rates by 22–45 kg N/ha (20–40 lb/ac) to winter wheat following cotton or grain sorghum production (Harris, 2013), presumably in recognition of N immobilization by highly carbonaceous residues. Ebelhar (1990) also recognized that cotton usually decreases available soil N to subsequent crops.

4 | WHEN SHOULD N CREDITS BE APPLIED?

In tropical countries, where peanut may be intercropped with nonlegumes, the N contribution to simultaneously grown corn has been estimated at 12%–26% of total corn N uptake (Senaratne et al., 1995). In this system, it is not clear how peanut contributes biologically fixed N to an adjacent plant since presumably biologically fixed N is translocated primarily to N sinks within the legume. It has been proposed that improved grass performance due to intercropping legumes is due to root excretion of nitrogenous compounds (Ruschel et al., 1979; Vest, 1971), root and nodule sloughing

(Butler & Bathurst, 1956), and N contributions from abscised leaves (Burton et al., 1983; Whitney & Kanehiro, 1967). Some authors also posit a so-called "N conserving effect," in which the lower uptake of soil N by legumes compared to cereals conserves soil N for cereal uptake (Janat, 1996; Senaratne et al., 1995).

Intercropping with peanut is seldom practiced in the United States, and there are typically 5–7 months (depending on the next crop) separating peanut harvest and the planting of the subsequent spring crop (but only 1–2 months if planting a winter crop behind peanut, e.g., Jani, Mulvaney, Erickson et al. [2020]. During that time, mineralization of peanut residue occurs in a double exponential fashion (Mulvaney et al., 2017), with subsequent loss of mineralized N during periods of no or little crop uptake. The synchrony between residue mineralization and subsequent crop uptake should be a primary consideration in order to maximize N credits from peanut. However, many states do not specify the subsequent crop to which the N credit should be applied or distinguish between N credits to fall-planted or spring-planted crops. For example, Virginia recommends 50 kg N/ha (45 lb N/ac) after peanut grown "under good conditions," but does not specify to which subsequent crop that N credit should apply. (Although the text of the soil test Extension bulletin mentions these N credits, they do not appear in the "comments" section of actual soil test reports for corn–peanut rotations [Maguire & Heckendorn, 2011, 2023], so growers may not see these comments on their soil test reports and thus largely fail to apply the recommended N credit.) Georgia recommends a 22–45 kg N/ha (20–40 lb N/ac) N credit from peanut to spring-planted crops (Kissel & Harris, 2015) but also recommends the same N credit to winter wheat planted in fall (Harris, 2013).

Peanut N contributions to winter wheat should be higher than to cotton or corn because wheat is grown temporally closer to the peanut harvest. On the other hand, it could be argued that it is cooler during the winter, so perhaps the N contribution to a spring-planted crop may be higher because of increased N mineralization rates due to the higher temperature as compared to a fall-planted crop. This last argument seems spurious, however, since the amount of time below biological zero, typically <5°C (Rabenhorst, 2005), is relatively short even at the northernmost limits of US peanut production. Given the double exponential decomposition dynamics of peanut residues (Jani et al., 2019; Mulvaney et al., 2017), N credits should be highest when crops are planted soon after the peanut harvest.

A related question arises about whether a peanut N credit should be applied to preplant or in-season N applications of the subsequent crop. We are not aware of any extension literature that addresses this question. For similar reasons mentioned above, the rapid mineralization of peanut residues implies that N credits would likely be most applicable to preplant N applications of the subsequent crop. This rapid mineralization of peanut residue may also lead to the "windrow effect" often observed after peanut, as discussed previously.

5 | DO N CREDITS DEPEND ON THE ENVIRONMENT?

Environmental effects that may affect N mineralization include climate, soil texture, and residue placement. With regard to climate, peanut residue N mineralization rates are slower in colder climates (Mulvaney et al., 2017). Since mineralization is slower in colder climates, less N is mineralized immediately following harvest, leaving a greater proportion of N available to be mineralized during the subsequent crop. Therefore, perhaps counterintuitively, colder climates are expected to have more mineralized N to the subsequent crop than warmer climates, thereby increasing synchronicity. However, potential N credits from peanut were small, regardless of location (Mulvaney et al., 2017).

Soils with higher clay contents (or soil organic matter) may retain mineralized N for longer periods than coarse-textured soils, an important consideration when considering litterbag studies. While litterbag studies determine the amount of N mineralized, they do not account for the nutrient-holding capacity of soils, which may potentially hold nutrients for sufficient periods to increase uptake by the subsequent crop. However, in the humid Southeast United States, there is consensus that available soil N is ephemeral and inorganic soil N at the time of planting is not available to the subsequent crop due to the warm climate, frequent leaching rainfall events, and sandy, low cation exchange capacity (CEC) soils (Breitenbeck, 1990; Pettiet, 1990). A laboratory incubation study using two common soil types for Georgia peanut production found that N mineralized from peanut residue applied to either soil type was not different from a soil-only control (Balkcom et al., 2004). On these common soils, the research indicates that N mineralization from peanut residue would not be a significant contributor to subsequent crop N uptake compared to soil alone.

Peanut residue left on the soil surface, such as in a conservation tillage system, may be expected to mineralize N at a different rate compared to incorporated residues. This effect is commonly observed for other residues regardless of climate or residue type (Cochran, 1991; Lynch et al., 2016; Mulvaney et al., 2010), and peanut is no exception. A litterbag study conducted in Florida investigated N credits to subsequent wheat and cotton crops under different simulated tillage regimes (Jani et al., 2019). At a reasonable peanut residue load of 4.5 Mg/ha (2.0 US tons/ac), the authors estimated potential N credits to a winter crop (wheat) at 34 kg N/ha (30 lb N/ac) when fall tillage was employed, compared to 24 kg N/ha (21 lb N/ac) under no-till. Potential N credits to cotton were estimated at 9 and 11 kg N/ha (8 and 10 lb N/ac) under spring tillage and no-till, respectively. The authors suggested that the faster rate of N mineralization observed from incorporated peanut residue compared to residues left on the soil surface was primarily due to the greater buffering capacity against changes in temperature and water content within the soil profile compared to the soil surface, though they could also be mineralized faster because of more intimate contact with soil microbes (Mulvaney et al., 2010).

6 | ARE N CREDITS DUE TO UNHARVESTED ROOTS, LEAF DROP, OR POD LOSS AT HARVEST?

Postharvest peanut root residue, containing N-fixing nodules, could conceivably contribute a substantial amount of N to a subsequent crop. Similarly, leaf drop, either from defoliation due to disease or during drying after windrowing and picking, could potentially contribute N to the subsequent crop. An incubation experiment using peanut straw at an average rate of 0.47 g N/kg soil (or approximately 950 lb N/6 in. acre furrow slice, a considerable amount) on a Chinese loess soil showed that peanut straw N mineralization was no different from the control, regardless of incorporation (Jin et al., 2008). Wheat straw, however, immobilized soil N providing further evidence that N immobilization, rather than mineralization, may explain differences in subsequent crop yield response to N rate after legumes versus nonlegumes. Notably, the only treatment with significant net N mineralization after 14 weeks was from incorporated peanut roots, while shoots were not different from the control regardless of incorporation or surface application. Since peanut shoots were no different from the control, this may indicate the importance of peanut root biomass for N credits. Although applied residue N rates were high, the results beg the question about peanut roots as the source of N credits and remain a researchable topic. Their results showing nonsignificant N mineralization from peanut straw are corroborated by other laboratory incubation studies conducted with US soils. Balkcom et al. (2004) found that above-ground peanut residue N mineralization was no different from a soil-only control on both a Tifton loam sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) and Greenville fine sandy loam (fine, kaolinitic, thermic Rhodic Kandiudult), common soils in the peanut-growing region of Georgia. The authors concluded that peanut residue does not contribute significant N to the subsequent crop on the soils tested. Further corroborating evidence was supplied by research that found peanut stems and a 1:1 mixture of leaves and stems mineralized N at the same rate as a soil-only control (Jani, Mulvaney, Balkcom, et al., 2020). Only peanut leaves contained higher net N mineralization compared to the control. These authors concluded that peanut leaves may contribute N to the following crop, but the amount would likely not be sufficient to replace mineral N fertilization.

Similarly, unharvested pods, which are likely to include a substantial amount of N-rich kernels nested with C-rich hulls, may also contribute to N credits. The effect may be accentuated in windrows where a larger proportion of mature pods remain on the ground after harvest. This may contribute to the "windrow effect," where increased growth of the subsequent crop is observed in former windrows. To date, there are no published studies that report the N contributions from unharvested pods, either in the field or in the laboratory. With approximately 8% pod loss at digging, and values reported up to 40% (Lamb et al., 2004; Rowland et al., 2006; Young et al., 1982), unharvested pods could be a significant N source. If this were the case, the C-rich hulls would be expected to delay net N mineralization, but the timeframe for that to occur remains unknown and is an area of active research. That said, the windrow effect on subsequent crop growth is typically most evident during the early season. That from pod N mineralization would likely become apparent much later. It is therefore unclear to what extent, if any, pod N mineralization contributes to N credits or the windrow effect, and this would certainly depend on the amount of pod loss at harvest. Additionally, many unharvested peanut seeds are preserved by the hull and emerge the subsequent year as volunteers. In summary, research indicates that peanut leaves and roots may supply some N to the following crop, but the amount is likely small and difficult to detect. Meanwhile, peanut shoots do not exhibit net N mineralization compared to soil-only controls.

7 | THE PRIMING EFFECT

The so-called priming effect (Hauck & Bremner, 1976), hypothetically caused by legume crop residue N mineralization, could feasibly be responsible for increased N made available to the following crop. A "priming effect" is observed when the addition of N to the soil stimulates the decomposition of native organic matter in the soil. The argument here would be that the addition of N-rich residue to soil stimulates microbial activity, thereby enhancing the mineralization of native soil N, such that N credits are not derived from residue alone but also from increased soil N mineralization. This question was cleverly addressed by Smith and Sharpley (1990) using both indigenous and ^{15}N-labeled soils in a laboratory incubation. The authors found that, in seven out of eight treatments, peanut residue did not significantly increase soil N mineralization compared to the control over a broad range of soil types. Although the study used air-dried and rewet soils, which is expected to reduce microbial biomass N and increase nutrient leaching from native soil (Gordon et al., 2008), the authors claimed evidence of a priming effect due to the addition of crop residues in general.

8 | CONCLUSIONS

There is a discrepancy between extension literature and peer-reviewed literature regarding N credits from peanut to the following crop. The peer-reviewed literature does not support current Extension recommendations and indicates that N credits are either insignificant or substantially lower than Extension recommendations. The amount of residue needed to make significant N contributions appears greater than can be reasonably expected at current peanut production levels. Crop growth and yield response following peanut compared to nonlegumes is likely due to N immobilization by non-leguminous residues rather than N mineralization (credits) from a previous peanut crop. Controlled environment studies show that net N mineralization from peanut residue is not different from soil-only controls. Field studies tend to corroborate these findings. Nitrogen contributions from roots, unharvested pods, and leaf drop after windrowing are unclear or remain uninvestigated but are unlikely to contribute significant N to the following crop. Nitrogen credits from peanut, if recommended at all, should take into account climate (more N credits applied in colder climates), tillage (more N credits from surface-placed residue compared to incorporated residue), residue load (or peanut yield as a proxy), and timing of the following crop (winter crops receive more N credits than summer crops). Removal of peanut residue from the field does not appear to affect N credits, such as they exist, to the following crop. Extension recommendations should be revised to reflect more modest N credits than those currently recommended, if they are recommended at all. Data on N loss pathways following peanut are needed to identify management strategies that might mitigate N losses after peanut harvest, improve environmental stewardship, and reduce mineral N fertilizer costs. As peanut yields (and residue loads) increase through continued breeding and agronomic progress, N credits may increase as a result.

AUTHOR CONTRIBUTIONS

Michael J. Mulvaney: Conceptualization; writing—original draft; writing—review and editing. **Joseph E. Iboyi**: Writing—review and editing. **Kipling S. Balkcom**: Writing—review and editing. **David Jordan**: Writing—review and editing. **Brendan Zurweller**: Writing—review and editing. **Arun Jani**: Writing—review and editing.

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