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RESEARCH ARTICLE

Adoption patterns of on-farm nutrient management practices and nitrogen application rates in California's Central Valley

Results from a nutrient management practices study show that most growers are adopting four or more practices in the same field.

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Abstract

Nitrogen fertilizers in irrigated agriculture improve cropland productivity, but contribute to groundwater contamination, air pollution, and greenhouse gas emissions. While California has implemented agricultural water quality regulations since the 1980s, targeted efforts to address nitrate contamination through nitrogen application reporting and management have been emphasized more recently under the Irrigated Lands Regulatory Program. This study uses a unique, field-level dataset from the Kings River Water Quality Coalition in California's Central Valley to examine nitrogen management practices, including common combinations of practices (bundling), across crop types. The analysis draws on four years of data from Irrigation and Nutrient Management Plans and details nitrogen application and management strategies. The results show that in 80% of fields across crops, between 50 and 300 pounds per acre (lbs/acre) of nitrogen is applied. Crop-level nitrogen applied minus nitrogen removed (A-R) values show substantial variation, with walnuts showing a nitrogen surplus (+65.5 lbs/acre) and alfalfa a significant deficit (−424.5 lbs/acre). Many growers adopt multiple practices, with 26% of fields utilizing six practices and 24% using five. Such bundling may provide growers with more flexibility in managing nitrogen applications. Further research is needed to evaluate the effect of various nitrogen management practices on fertilizer use and water quality effects.

California is a leader in agricultural production. Yet, in the 21st century, the agricultural sector in California faces challenges from water scarcity, regulatory pressures, environmental degradation, economic competition, and climate change (Kishore et al. 2025). Nitrogen-based fertilizers play a crucial role in sustaining crop yields in industrialized agriculture, and their use has increased over the past few decades. From 1973 to 2005, as crop yields have generally risen, 75% of crop types in California saw increases in nitrogen application rates (Ligon 2011; Rosenstock et al. 2013).

While sufficient nitrogen (N) fertilizers are almost always applied to support agricultural productivity, particularly to help crops reach their yield potential, their benefits depend on crop needs and other limiting factors. When over-applied, N fertilizers can contaminate waterways, groundwater, and air quality, and contribute to greenhouse gas emissions that drive climate change (Harter et al. 2012; Kanter et al. 2020; Osmond et al. 2015). Groundwater contamination, in particular, disproportionately affects economically disadvantaged rural communities that rely on well water for drinking (Harter et al. 2012).

A tractor sprays fertilizer on a field of young wheat. Most annual nitrogen applications (80%) range between 50 and 300 lbs/acre, with few fields receiving amounts beyond 300 lbs/acre. *Photo*: Lenoid Eremeychuk, iStock.com.

On average, five out of eight practices are implemented by a grower in the same field, with citrus crops with high nitrogen demands adopting the most practices.

Recognized effects of nitrate contamination from fertilizer use have prompted regulatory efforts to address surface water and groundwater quality. Since 1982, programs by the California State Water Resources Control Board (State Water Board) have sought to reduce pollution from agricultural fields through permits issued under the authority of the Porter Cologne Water Quality Control Act (SWRCB 2024). In 2003, the State Water Board implemented the Irrigated Lands Regulatory Program (ILRP) to promote consistent monitoring of surface water quality impacts from agricultural runoff and, where appropriate, require actions by landowners to reduce pollution. Following a decade of policy developments and legal challenges to the ILRP, in 2013, the Central Valley Regional Water Quality Control Board identified nitrates as a significant threat to water quality and updated the program to include new requirements to protect both surface water and groundwater. The same year, the California Department of Food and Agriculture (CDFA) convened a task force (CDFA 2013) to provide recommendations for tracking fertilizer use.

In 2014, the State Water Board convened an Agricultural Expert Panel, which recommended regulatory strategies aimed at improving nitrogen management to reduce nitrate loading into groundwater, particularly in areas where contamination levels pose a risk to drinking water quality. This marked a shift from reactive groundwater monitoring to a more proactive approach targeting reductions in nitrate leaching through improved management practices and enhanced reporting (SWRCB 2014). By 2018, the State Water Board had extended regulatory measures to multiple regional water quality boards in California, mandating growers across the state to report nitrogen application (A) and removal (R) from croplands. (There are nine regional water quality boards in California; see the directory for details.) These reporting requirements aim to track nitrogen use efficiency and mitigate environmental impacts by employing two alternative metrics: the efficiency ratio (A/R) that is unitless, and a simple mass balance of excess nitrogen (A-R).

Today, California's agricultural producers (growers) must comply with self-reporting requirements that seek improvements in the efficiency of fertilizer application. Many California growers have implemented nutrient management practices (NMPs) to increase efficiency and comply with regulatory requirements. Training and extension programs have supported growers in adopting best practices. When deciding among NMPs, growers consider factors such as crop type, soil conditions, expected yield, operational and material costs, and regulatory requirements. They also make decisions within a broader context that encompasses experience, preferences, farm characteristics, and numerous other factors (Rudnick et al. 2023). NMPs can be adopted by growers either as single management practices or as bundles, where multiple management practices are used in combination. Bundling refers to the adoption of several complementary practices that work together to enhance nitrogen management (Reints et al. 2020).

Installing soil moisture sensors at an on-farm pistachio demonstration trial in Fresno County. *Photo:* Ben Halleck.

The ILRP and similar efforts in California aim to balance the benefits of fertilization and the need to mitigate environmental impacts. More than a decade has passed since the program's implementation, and the ILRP is creating comprehensive datasets of nitrogen application rates and practice adoption at the field level. This will enable a detailed evaluation of trends in nitrogen application and efficiency as regulations are implemented. Analysis of the data collected through the ILRP can help evaluate its effectiveness and understand progress towards grower adoption of improved fertilization practices.

Few studies have examined the prevalence of different NMPs among growers in California and the extent to which, if any, growers adopt multiple practices (Sears et al. 2023). To address this gap in research, this study assesses (a) trends in nitrogen application over time, (b) adoption of NMPs by crop categories and (c) adoption of bundles of NMPs by crop categories. By analyzing nitrogen application within California's evolving regulatory environment, we aim to provide evidence-based insights that can help inform policy interventions and guide growers toward more sustainable and efficient nitrogen use strategies.

Nitrogen management data

Since 2021, growers in California's Central Valley have reported nutrient management practices and applications through an annual Irrigation and

Nitrogen Management Plan (INMP) to comply with ILRP requirements. Grower-led coalitions collect and analyze data from these plans, which aggregate the information and in the Central Valley, anonymize data. Such efforts are critical for understanding regional nitrogen application trends, compliance with regulatory metrics, and the effectiveness of current nitrogen management strategies. Datasets of INMP reporting span multiple counties and diverse agricultural landscapes within California, covering numerous types of crops and farming practices. Within the Central Valley, data are collected from 14 water quality coalitions. Growers usually self-report data in compliance with INMP requirements.

Kings River Water Quality Coalition

The Kings River Water Quality Coalition (KRWQC), the focus of this study, is one of 14 coalitions operating in California's Central Valley, covering major portions of Fresno, Kings and Tulare counties within the Kings River watershed (fig. 1). This region, encompassing parts of the Kings and Tulare Lake subbasins, includes surface water bodies like the Kings River and Fresno Slough, as well as a complex network of irrigation and recharge infrastructure. Cities such as Fresno, Hanford and Lemoore lie within its boundaries. The area relies heavily on the Kings River, with Pine Flat Reservoir providing services such as storage, flood control, and hydropower generation. Most crops in the region are irrigated, covering approximately 760,000 acres. The dominant crops include almond, pistachios, citrus, vineyards and walnuts.

We analyzed trends in total nitrogen application rates and adopted NMPs using INMP reporting data from the KRWQC. The KRWQC dataset includes a panel of anonymized, field-level data on crop types (e.g., almond, pistachios, citrus and vineyards), nitrogen management practices, application rates, and efficiency.

In ILRP reporting, growers select from a list of eight management practices to indicate what is used in their operations. There are two main sets of related practices: testing practices and application practices. *Testing practices* assess nitrogen levels in soil, plant tissue, and irrigation water, enabling growers to determine the current nitrogen levels in their fields and apply additional nitrogen more precisely to reduce excess leaching (Ulrich-Schad et al. 2017). *Application practices* improve fertilizer application and include a range of techniques: foliar application involves applying fertilizer directly to plant leaves for quick absorption; variable rate application uses advanced technology to apply nitrogen at variable rates based on soil type and conditions; cover crops maintain winter or summer vegetation cover in dormant fields to promote soil health, capture available soil nitrate, and reduce erosion; split nitrogen application applies nitrogen in multiple doses throughout the growing season to maximize plant uptake and reduce losses; and fertigation incorporates fertilizers into the irrigation system.

Though the nitrogen cycle is more complicated, two practical metrics have been used to evaluate nitrogen use based on rates of nitrogen applied (A) and nitrogen removed (R). First, the ratio of amount applied to amount used (A/R) is a measure of the relative efficiency of nitrogen applications. Second, the difference between nitrogen applied and used (A-R) estimates the total excess nitrogen applied, thus directly informing efforts to reduce nitrate leaching into groundwater (SWCRB 2014). A positive A-R value or a value of A/R greater than 1 suggests that more nitrogen was applied than removed, indicating excess nitrogen that could lead to runoff or leaching. Table 1 summarizes key

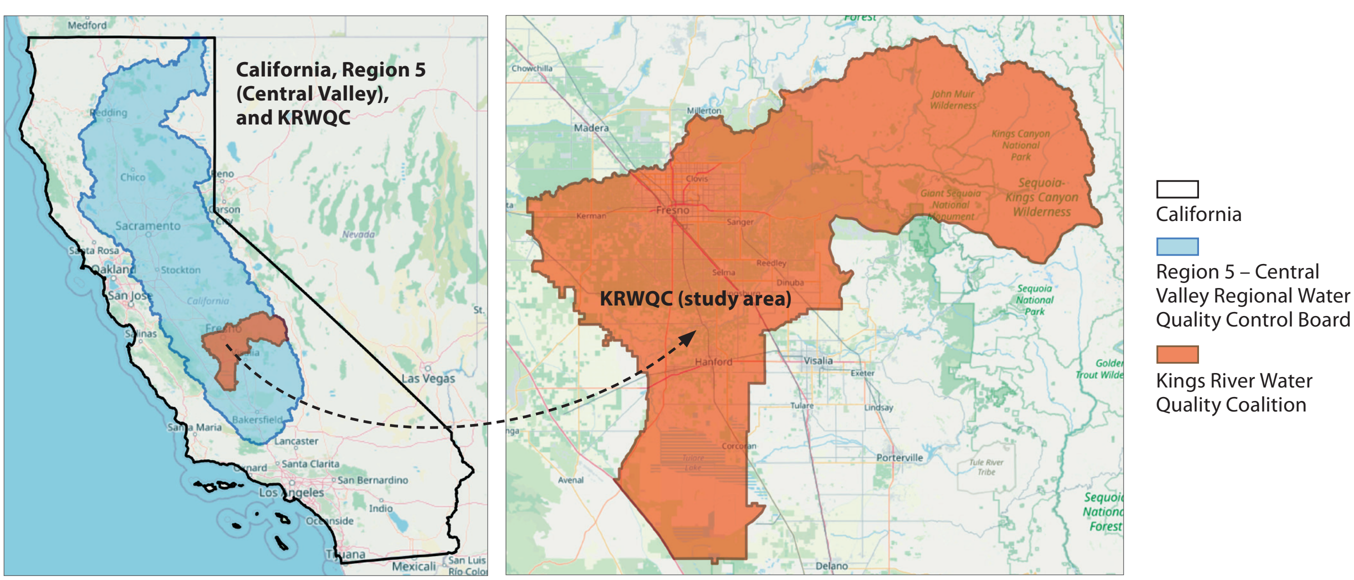

FIG. 1. Region 5 – Central Valley Regional Water Quality Control Board (left) and Kings River Water Quality Coalition (right).

variables used in our analysis, including definitions, units and time periods for each variable.

Crop types

Our dataset includes 94 different crop types harvested within the KRWQC region. For this analysis, we grouped these crops into 11 categories based on their nitrogen needs (see table A1 in the online technical appendix). This classification approach reflects agronomic similarities related to nitrogen use and management practices. Citrus crops were grouped into those of higher nitrogen demands (such as lemons and oranges) and those of lower nitrogen demands (such as grapefruit). It is important to recognize that nitrogen requirements, cultural practices, and nitrogen removal rates vary considerably across crop types and fields. These agronomic differences were carefully considered during the crop grouping process to enhance the interpretability of nitrogen management practices within each category. Almond, pistachios, walnuts, orchard crops, citrus and vineyards collectively account for 92% of the total acreage across the 94 crops, while the remaining crops represent just 8%. Therefore, starting with table 2, our analysis focuses exclusively on the crops comprising this dominant 92%.

Nitrogen applied

For the years 2019–2022, a total of 3,401 growers covering nine crop categories submitted INMP reports, with an average total nitrogen applied of 93.6 pounds per acre (lbs/acre). As shown in table 2, there is substantial variation in nitrogen application rates across different crop categories. On average, almond received the highest nitrogen application rates at 152.4 lbs/acre, followed by walnuts (119.7 lbs/acre), pistachios (102.6 lbs/acre) and citrus crops with high N requirements (101.3 lbs/acre).

Lower average nitrogen application rates were associated with citrus (low N requirement) crops at 66.6 lbs/acre, orchard (high and low N requirement) crops at 61.6 lbs/acre and 58.3 lbs/acre, and vineyards at 51.7 lbs/acre. Alfalfa, known for its nitrogen-fixing capabilities, has one of the lowest application rates at 26.8 lbs/acre. These rates reveal the lower nitrogen requirements of certain crops but may also reflect efficiency improvements in NMPs by growers. Understanding these differences is crucial for developing crop-specific nitrogen management strategies that optimize nitrogen use efficiency.

Figure 2 presents violin plots that illustrate the distribution of total nitrogen applied (TNA) across all crop types in the study area. The width of each violin at a given TNA value reflects the density of fields applying that level of nitrogen; wider sections indicate more fields with similar nitrogen application rates, while narrower sections indicate fewer fields. The plots provide a visual understanding of both the spread and concentration of nitrogen application rates across the dataset.

For all crops, the distribution of total nitrogen applied across four years was consistent, as shown in figure 2. Most annual nitrogen applications (80%) range between 50 and 300 lbs/acre, with few fields receiving amounts beyond 300 lbs/acre. The broader spread of nitrogen applied in earlier years becomes slightly more concentrated in later years, suggesting two subtle shifts in nitrogen management practices: more growers are applying a similar amount of nitrogen, and fewer are applying high rates of nitrogen (especially between 175 and 250 lbs/acre).

Calculating A-R values in the dataset revealed notable differences across crop types (table 2). For instance, walnuts show a relatively high average excess nitrogen (A-R) rate of 65.5 lbs/acre, suggesting substantial nitrogen surplus but does not consider residual nitrogen storage in perennial tissues. In contrast, alfalfa crops exhibit a significantly negative A-R value of −424.5 lbs/acre. This negative A-R value for alfalfa is expected, as it is a nitrogen-fixing crop with lower nitrogen requirements.

Reported nitrogen management practices

Among all growers, 5.5% reported using only testing practices, 8.5% used only application practices, and the vast majority, 86%, used a mix of both. Among

TABLE 1. Summary of variables in this analysis

Variable	Definition	Units	Years available
Crop type	Types of crops grown in each field (e.g., almond, vineyards, citrus, etc.)	Categorical (crop type)	2019–2022
Nitrogen applied (A)	Amount of nitrogen fertilizer applied per acre. It includes nitrogen applied via fertilizers, organics and compost, and irrigation water.	pounds/acre	2019–2022
Nitrogen removed (R)	Nitrogen removed through crop yield	pounds/acre	2019–2022
Nitrogen efficiency (A-R)	Difference between the nitrogen applied (A) to a crop and the nitrogen removed (R) from the field	pounds/acre	2019–2022
Irrigation technologies	Types of irrigation used: surface, sprinkler, drip, furrow	Categorical	2022
Nutrient management practices	Various nutrient management practices employed by growers	Categorical	2022

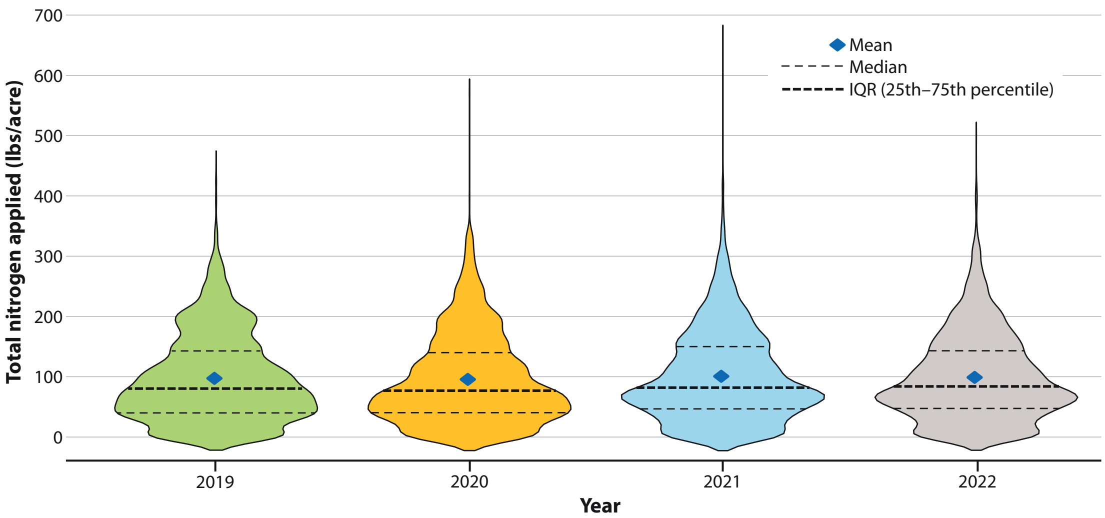

FIG. 2. Violin plots of total nitrogen applied by years across all fields and crops. IQR = interquartile range.

TABLE 2. Summary statistics of total nitrogen applied (TNA) and nitrogen efficiency (A-R) by crop categories, 2019–2022

Crop type	Observation	TNA (lbs/acre)		A-R (lbs/acre)	
		Mean	Standard deviation	Mean	Standard deviation
Alfalfa	731	26.8	38.6	−424.5	332.9
Almond	11,135	152.4	82.0	21.6	72.5
Citrus (high N demand)	10,262	101.3	54.9	64.7	55.0
Citrus (low N demand)	419	66.6	61.2	43.7	53.7
Orchard (high N demand)	7,674	61.6	39.9	30.8	43.2
Orchard (low N demand)	3,481	58.3	41.3	40.3	43.1
Pistachios	2,449	102.6	67.7	28.6	1312.3
Vineyards	9,434	51.7	43.0	29.0	85.3
Walnuts	2,618	119.7	66.4	65.5	60.9
All crops	48,203	93.6	70.6	30.9	305.6

Note: "All crops" includes the top 92% crops (alfalfa, almond, pistachios, walnuts, orchard crops, citrus and vineyards accounting for 92% of the total acreage of crops grown in the KRWQC).

reported testing practices, soil testing is the most widely adopted, with 77% of fields using this practice. Other testing practices are also widely adopted: tissue testing is used at 73% and irrigation water testing at 72% (fig. 3).

In the application practices category, split nitrogen application is the most adopted at 78% of the fields. Fertigation has a high adoption rate of 60%, foliar nitrogen application is at 51%, cover cropping practices have been adopted by only 13%, and variable rate application of fertilizers is the least adopted practice (1%), likely reflecting technological and financial barriers (fig. 3).

There are also variations in the practices adopted across various crop types (fig. 4). In all types of citrus (both low and high N requirement varieties), variable rate nitrogen application is the least adopted practice with fewer than 0.05% of fields utilizing it, while in almond, pistachios, and walnuts it is adopted by only 2%, 3% and 0.8% of fields, respectively. Conversely, split nitrogen application is the most adopted practice, with

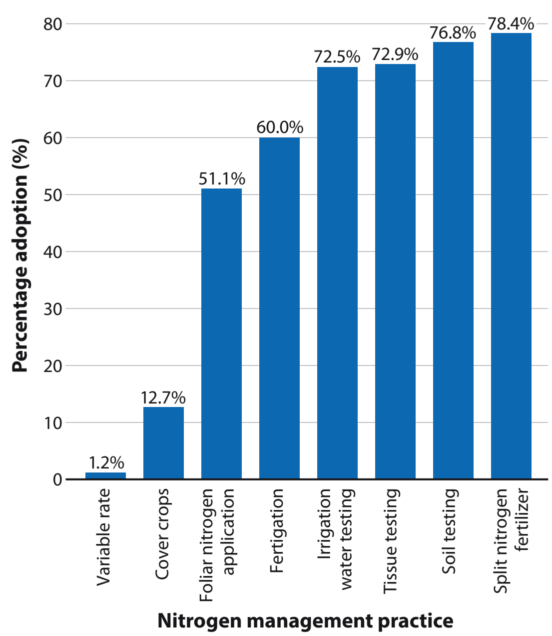

FIG. 3. Percentage of nitrogen management practices adopted across fields.

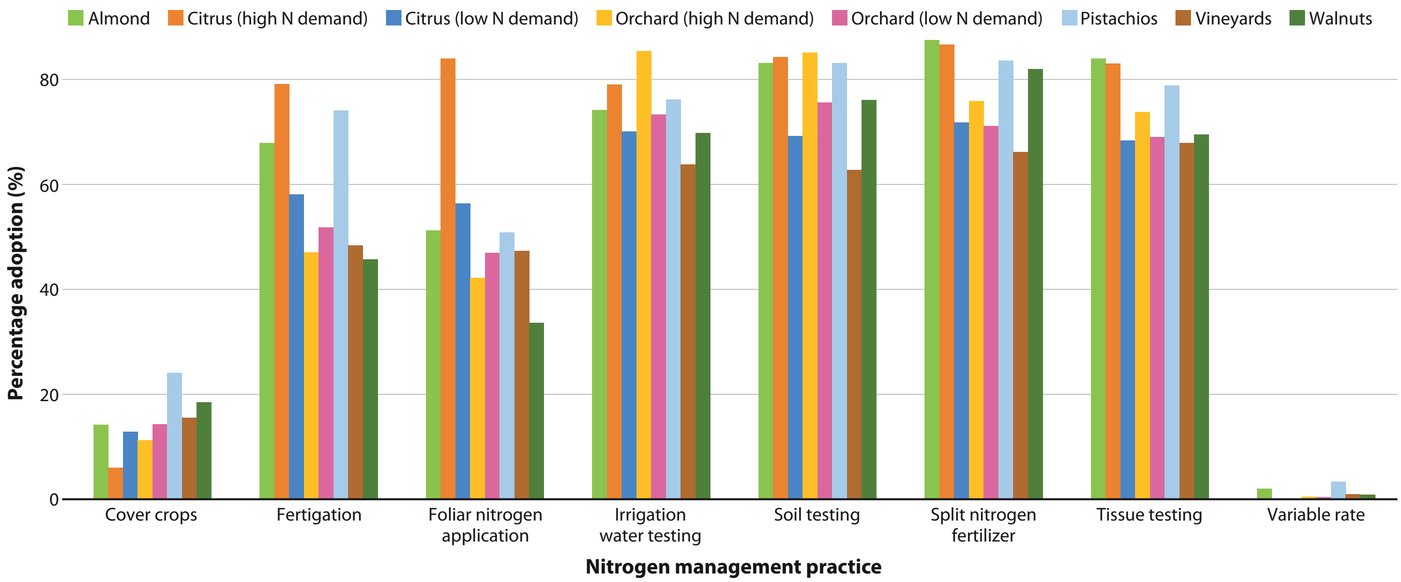

FIG. 4. Adoption rates of nitrogen management practices by crop categories.

an adoption rate of 88% in almond, 87% in citrus (high N requirement), 83% in pistachios and 82% in walnuts. The remaining practices fall between these extremes, with six out of the eight practices being adopted by more than half of the fields in all crop categories.

For orchards (apples, apricots, cherries, peaches, plums and other fruit) and vineyards, variable rate nitrogen application is the least adopted practice, used in only 0.3% of orchard (low N demand) fields, 0.4% of orchard (high N demand) fields, and 0.9% of vineyard fields. Among orchards, the most widely adopted practices are soil testing (85% in high N requirement orchards and 76% in low N requirement orchards) and irrigation water testing (85% and 73%, respectively). In vineyards, tissue testing is the most commonly adopted practice, with a 68% adoption rate. Adoption rates for the remaining practices vary, but four out of the eight NMPs are implemented by more than half of the fields in both orchards and vineyards.

Additional context on irrigation methods reported by growers helps clarify the low prevalence of variable rate applications. High adoption rates of drip and microsprinkler systems among tree crops and vineyards constrain the feasibility of implementing variable rate nitrogen technologies. Specifically, drip and microsprinkler irrigation is used on 78% of almond fields, 92% of pistachio fields, 94% of high N requirement citrus fields, 79% of low N requirement citrus fields, 42% of high N requirement orchard fields, 57% of low N requirement orchard fields, 60% of vineyard fields, and 31% of walnut fields. While highly efficient at delivering water and fertilizer, these irrigation systems apply them evenly across the irrigation blocks. This uniform application limits the differences in soil or plant conditions within the field — differences that are necessary for variable rate technologies to work effectively. As a result, we observed low adoption rates of variable rate technologies among these crops.

Adoption of multiple NMPs by growers is an indicator of how growers are responding to regulatory requirements and policy goals for sustainable farming practices. Adoption of multiple NMPs is widespread, which emphasizes that growers rarely rely on single practices (fig. 5). A notable 26% of fields adopted six different NMPs, while 24% of fields implemented five NMPs. Interestingly, only 8% of fields adopted a single NMP, and a small proportion, 3%, adopted none of the eight NMPs.

The data shows that the adoption patterns differ significantly depending on the crop grown. For instance, in citrus crops with high N requirements, 53% of growers adopted six different NMPs, and another 19% of growers adopted five NMPs. This high level of adoption suggests that growers of citrus crops, which have a high nitrogen requirement, prioritize integrated strategies,

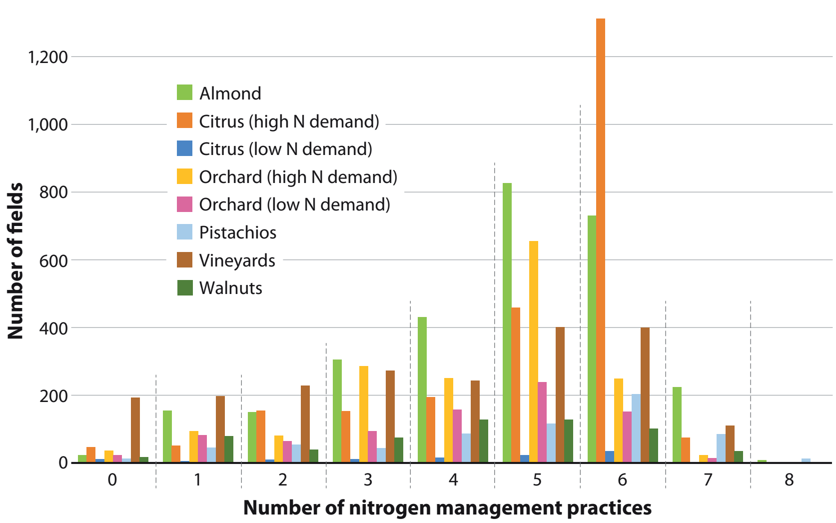

FIG. 5. Adoption of nitrogen management practices bundles by crop categories.

even though these crops have moderate nitrogen and water requirements compared to other major crops, such as almond, walnuts and pistachios. For orchard (high N requirement) crops, adoption patterns show that more growers favor slightly fewer NMPs. Here, 39% of growers adopted five NMPs, with 17% adopting three and 15% adopting four NMPs. Growers of almond, pistachios, vineyards and walnuts show similar adoption rates of NMP practices: 29% of almond, 18% of pistachios, 20% of vineyard and 21% of walnuts growers adopted five NMPs, while 26% of almond, 31% of pistachios, 19% of vineyard and 17% of walnuts fields adopted six NMPs. This consistency in NMP adoption patterns across two very different crops might reflect common concerns about water and nitrogen use efficiency in these systems.

Growers predominantly use more than one nitrogen management practice (table 3). On average, five out of eight practices are implemented by a grower in the same field, with citrus crops with high N demands adopting the most practices. In contrast, alfalfa crops exhibit low adoption, with only two practices on average. The low adoption rates of NMPs for alfalfa crops are expected, given the crop's nitrogen dynamics. Based on the data, approximately 51% of nitrogen inputs for alfalfa fields originated from irrigation water, while only 42% came from fertilizer applications. Alfalfa's ability to fix atmospheric nitrogen reduces its need for synthetic fertilizers. Therefore, the practicality of practices such as fertigation, foliar N applications, split N fertilizer, and variable rate applications is limited in alfalfa production systems. Cover cropping is also not a feasible option in perennial alfalfa fields. These agronomic characteristics help explain the observed lower adoption rates among alfalfa growers.

Practices are co-adopted, but not consistently (fig. 6). A correlation matrix reveals which NMPs tend to be adopted together, with positive values indicating a tendency for practices to be adopted together, while negative values suggest an inverse relationship. Figure

TABLE 3. Summary statistics (mean, ± standard deviation) for implemented practices and nitrogen use by crop category, 2022

Crop	Obs.	No. of practices adopted	Total N applied (lbs/acre)
Alfalfa	253	2.0 (±1.6)	23.7 (±38.7)
Almond	2,855	4.6 (±1.6)	145.4 (±79.2)
Citrus (high N requirement)	2,448	5.0 (±1.5)	104.1 (±53.6)
Citrus (low N requirement)	117	4.0 (±2.0)	88.3 (±63.3)
Orchard (high N requirement)	1,677	4.2 (±1.5)	70.0 (±40.4)
Orchard (low N requirement)	828	4.0 (±1.7)	64.1 (±43.7)
Pistachios	663	4.7 (±1.9)	95.5 (±65.2)
Vineyards	2048	3.7 (±2.1)	53.4 (±44.8)
Walnuts	606	4.0 (±1.9)	109.2 (±59.1)
All crops	11,495	4.4 (±1.8)	94.9 (±68.3)

Note: "All crops" includes the top 92% crops (alfalfa, almond, pistachios, walnuts, orchard crops, citrus and vineyards accounting for 92% of the total acreage of crops grown in the KRWQC).

	Cover crops	Fertigation	Foliar N application	Irrigation water testing	Soil testing	Split N fertilizer	Tissue testing	Variable rate application
Cover crops	1.00							
Fertigation	0.01	1.00						
Foliar N application	0.03	0.23	1.00					
Irrigation water testing	0.05	0.25	0.20	1.00				
Soil testing	0.07	0.27	0.24	0.48	1.00			
Split N fertilizer	0.05	0.34	0.24	0.28	0.31	1.00		
Tissue testing	0.07	0.34	0.31	0.38	0.57	0.43	1.00	
Variable rate application	0.04	0.04	–0.01	0.03	0.05	–0.05	0.03	1.00

FIG. 6. Correlation matrix of nitrogen management practices.

Adoption of multiple nitrogen management practices by growers is an indicator of how growers are responding to regulatory requirements and policy goals for sustainable farming practices.

A forage mower harvests alfalfa. *Photo:* selobg, iStock.com.

6 presents the pairwise correlation coefficients between different nitrogen management practices using a color gradient to represent both the strength and direction of the relationship. Dark blue shades indicate a strong positive correlation (closer to +1), meaning that two practices are often adopted together, while dark red shades indicate a strong negative correlation (closer to −1), suggesting that adoption of one practice is associated with non-adoption of the other. Lighter shades represent weaker relationships closer to zero, implying little or no association between practices. Specifically, correlations between 0.5 and 1 indicate a moderate to strong positive relationship, while correlations below 0.5 suggest a weak positive relationship.

Of co-adopted practices, for instance, nitrogen testing in both soil and water exhibits a positive correlation ($r = 0.48$), indicating that fields employing soil testing are 48% more likely to also implement water testing. Similarly, tissue testing of nitrogen shows moderate positive correlations with both soil testing ($r = 0.57$) and irrigation water testing ($r = 0.38$). The robust correlations between these practices likely stem from the common practice of hiring a certified crop advisor (CCA) or consultant, who typically conducts all three tests — soil, tissue and irrigation water testing — as a bundled, cost-effective service.

In contrast, weak negative correlations are observed between certain practices, such as variable-rate application and split nitrogen fertilizer ($r = -0.05$). A weak negative correlation between variable-rate technology and split fertilizer applications likely reflects the crop composition of our sample, where 92% of observations are tree crops and vineyards. In these systems, fertigation through drip or microsprinkler irrigation is common, making variable-rate applications technically challenging and rarely used. The low adoption of variable-rate technology in perennial systems is due to infrastructural constraints. This may reflect that growers adopt these practices independently based on field-specific conditions or crop management needs, rather than as part of a uniform strategy.

Policy implications

More than a decade has passed since expert panels recommended monitoring programs and data collection rubrics that promote efficient nitrogen use in California's agricultural fields. Data collected through the ILRP reveal trends over time in the practices that growers adopt in response to requirements.

Our results highlight the prevalence of using multiple practices to improve nitrogen management. Most growers in the case study region are adopting four or more NMPs in the same field, signaling expectations for the benefits of integrated strategies. The variation in NMP use across crop types may suggest that growers and their consultants are making choices about how to combine NMPs based on the specific needs of their crops, but this requires more investigation through outreach and interviews. The data clearly show that some bundling practices are commonly adopted.

These insights emphasize the importance of broader context when investigating how growers make decisions about NMPs. This knowledge can be valuable information for extension advisors and consultants who work closely with growers, and whose input helps ensure that growers are not only complying with regulations but also optimizing their crop management strategies.

While our study focuses on descriptive trends in adoption patterns and nitrogen application rates, future research will build upon these findings by estimating the effectiveness of adopting multiple NMPs relative to a single NMP in reducing nitrogen application rates and examining correlations with sources of irrigation water when reported. This planned analysis will allow for a more rigorous evaluation of the potential incremental benefits of practice bundling for improving nitrogen use efficiency.

Continued long-term data collection is crucial to track trends in nitrogen use and assess the impact of NMP adoption on nitrogen use efficiency. Growers play a central role in this effort by completing INMPs and funding coalition activities that support monitoring and reporting. Regulatory and policy agencies should continue to complement these grower-led investments by supporting longitudinal data collection and analysis efforts that enable year-over-year comparisons, which could help determine whether NMP adoption improves nitrogen use efficiency and protects water quality. Collecting grower-specific data, such as farm characteristics, grower characteristics, and socioeconomic factors, would provide deeper insights into adoption patterns and help tailor support to different farming communities. CA

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