



Agronomic factors are the dominant influence on nitrogen fertilizer strategies in dryland cropping systems

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Abstract

Factors affecting fertilizer decisions made by grain growers are changing in the context of changing climatic conditions and growing volatility in global fertilizer and grain markets. To ensure sustainable development of grain industries in light of this uncertainty, research, development, extension, and adoption activities associated with growers' fertilizer decisions need to be focused on factors to which they are most sensitive. The aim of this paper is to understand the factors that have the greatest influence on grain producer's fertilizer strategies, how these factors have changed over recent years, and what is the relative importance of agronomic, socioeconomic, and logistical factors affecting these strategies. A telephone survey of 425 grain-growing businesses in Western Australia was conducted, and survey results were analyzed statistically. We show for the first time that grain growers' fertilizer decisions are most sensitive to agronomic factors (especially the amount and distribution of rainfall). Logistic factors (such as difficulties fertilizing increasing areas in short periods of time) are growing in influence as farm size, cropping areas, and the number of fertilizer applications within seasons increase. Fertilizer decisions have become less sensitive to socioeconomic factors over the last 10 to 15 years. To ensure sustainable development of grain production, research through to adoption activities should focus on agronomic issues (such as seasonal forecasting) and logistic issues (such as improving planning, organizational, and technical capacity for developing and implementing fertilizer strategies).

Keywords Fertilizer decisions · Agronomic · Socioeconomic · Logistics · Australia

1 Introduction

Globally, nutrient application rates on agricultural land are increasing (Pellegrini and Fernandez 2018). For example, from 1961 to 2018, global nitrogen (N) fertilizer use increased from 3 to 26 kg N/ha (FAOSTAT 2021). This

increase has been driven by global population growth and the associated increase in demand for food to be produced on decreasing areas of arable land (Bindraban et al. 2015). As a result, fertilizer costs are a growing proportion of total costs and an increasingly important determinant of farm profit (AgSurf 2021; Brunelle et al. 2015; Monjardino et al. 2013; Nti 2022). Fertilizer costs are a large expense, especially in regions with relatively large farm size and cropping programs (AgSurf 2021) (Fig. 1).

A number of studies have considered global trends which are likely to shape agriculture and therefore fertilizer use over the coming decade (for example, Hatfield-Dodds et al. 2021; EC 2019; FAO 2017 and Kingwell and Pannell 2005). Five trends are of specific importance for fertilizer use in grain production globally. These include (1) the shift in the economic, military, and cultural power which are expected to make international trade and relations more complex; (2) the increasing need for continuous innovation to drive productivity improvements and maintain farm incomes; (3) the accelerating changes in climate systems leading to

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Fig. 1 Urea application to wheat on a farm in Western Australia. Photo credit: Angie Roe Photography.



increased volatility in climatic conditions and commodity prices; (4) the exponential advance in digital technology, automation, genetics, and synthetics; and (5) the trend for carbon neutrality and accounting for food production. These five factors are expected to lead to increased use and efficiency of fertilizer to maintain export competitiveness and farm incomes, a rise in the riskiness of fertilizer decisions, and a growing focus on fertilizer applications to manage farm income volatility.

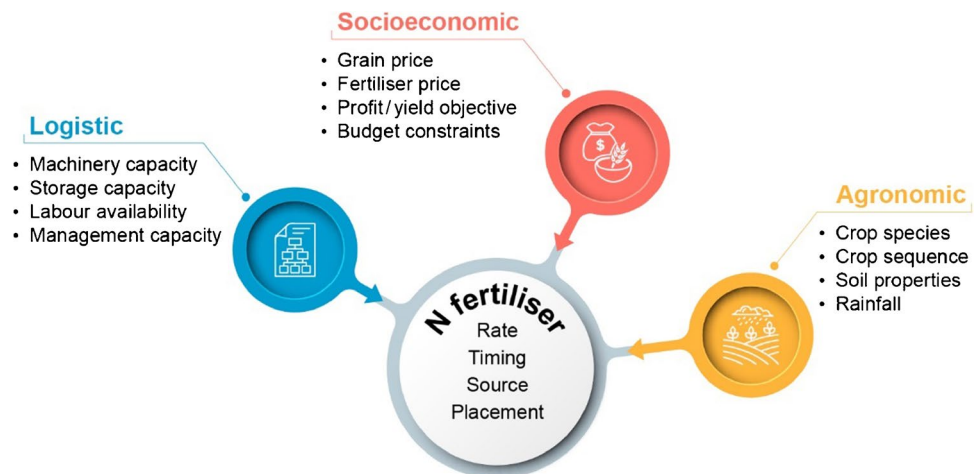
These trends emphasize that the sustainable development of grain production will rely increasingly on grain growers' ability and willingness to employ improved approaches when planning and implementing fertilizer strategies. Poor planning and implementation can put at risk sustainable development by preventing productivity growth from outstripping the negative impacts of climate

and market volatility on yields. In turn, this prevents the maintenance of farm income and leads to over-contributing to carbon emissions in light of these risks.

In developing fertilizer strategies, producers are making decisions about the number of times fertilizer is applied to the crop over the growing season, the rate of fertilizer applied each time, the timing of applications, the form in which fertilizer is applied (such as granular or liquid), and the depth of application. These decisions are interdependent and are influenced by a number of agronomic, logistic, and socioeconomic factors (Fig. 2).

Agronomic factors include the type of crop, crop sequence, the type and variability of soil conditions, and the amount and distribution of rainfall (Pannell 2017). Different crop types (e.g., cereals, oilseeds, and pulses) require different types and rates of fertilizers applied at

Fig. 2 Map of the factors that influence fertilizer application strategy.



different phases of crop development (Hirel et al. 2011). Crop and pasture legumes fix nitrogen in the soil, reducing nitrogen fertilizer requirements for subsequent crops (Preissel et al. 2015). Soil type, the amount and distribution of rainfall, and stored soil moisture are also important agronomic issues as they affect the potential yield and therefore fertilizer requirements of crops (Oliver and Robertson 2009; Schwenke et al. 2018).

Socioeconomic issues include the price of grain, the price of fertilizer, the aims of the producer, and their attitude towards risk. The economically optimal fertilizer rate depends on the ratio of fertilizer price to grain price (Bachmaier and Gadorfer 2012). If this ratio is relatively small (the price of fertilizer is low compared with the price of grain), then the economically optimal rate of fertilizer is higher than when the ratio is relatively high (the price of fertilizer is high compared with the price of grain) (Dillon and Anderson 2012). In addition, the aim of the producer may not be purely to maximize profit. They may also be concerned with reducing risk, easing management load, and minimizing environmental impacts, which also affect the amount of fertilizer applied (Pannell 2017).

Logistical issues such as planning, organizational, and the technical capacity required to ensure crop areas are fertilized within a short period (i.e., before an expected rainfall event), are becoming increasingly important factors influencing a producer's fertilizer strategy. The importance of these issues is increasing as a result of advances in innovation and technology, growing farm sizes, larger cropped areas per farm, and associated increasing machinery and input requirements (Fletcher et al. 2016; Saiz-Rubio and Roviro-Mas 2020). Logistical issues include the use of fertilizer within a growing season to minimize storage requirements, refilling fertilizer equipment efficiently to minimize downtime, and limitations to the size and number of compartments for fertilizer in seeding equipment.

A clear understanding of evolving fertilizer decision-making processes from a farm business perspective is important to ensure that research, development, extension, and adoption activities are appropriately targeted to ensure the sustainable development of grain production. This is becoming increasingly important within the context of the rising volatility of climatic conditions and global markets. The research questions addressed in this study are the following:

- What factors have the greatest influence on fertilizer strategies?
- How have these factors changed over recent years?
- What is the relative importance of agronomic, socioeconomic, and logistical factors affecting these decisions?

2 Materials and methods

To address these research questions, a case study of grower fertilizer strategies in grain-growing regions of Western Australia was used as a case study. The focus of the study is Western Australia. This is the State of Australia with (1) the greatest area and volume of wheat production, (2) the greatest increase in farm size over the last 30 years, (3) the greatest decline in growing season rainfall over the same period, and (4) the greatest impact of climate change on farm business profit (ABARES 2022a; AgSurf 2021; Hughes et al. 2019; Hatfield-Dodds 2019; Scanlon and Doncon 2020). Wheat is the focus of the case study as it accounts for most of Australia's grain production (ABARES 2022b). The study focuses on mineral fertilizers, rather than organic fertilizers; and conventional wheat production, rather than organic wheat production. Conventional wheat production accounts for approximately 99.9% of wheat production in Australia (Byrne 2017).

2.1 Sample, distribution, and design

Grain producers' views about the factors influencing their fertilizer decisions were elicited through a telephone survey conducted in September 2020. The survey focused on managers of grain-producing businesses in Western Australia, of which there are currently about 3900 (ABARES 2020), which represents approximately 27% of grain businesses in Australia. The survey had an aim of surveying 400 grain businesses—about 10% of Western Australian grain-producing businesses. A sample population was extracted from a database of grain-producing businesses using a stratified sampling approach to ensure representation from the four port delivery zones; Albany, Esperance, Geraldton, and Kwinana (Fig. 3). Targets for the number of respondents from each port zone were based on the relative area of each port zone (Table 1).

The survey was completed by telephone interview, following the requirements for market, opinion, and social research outlined by the International Organization for Standardization (ISO) (ISO 2019). Prior to the survey being conducted, each respondent in the sample population was contacted by email and provided an opportunity to decline from participating in the survey. No incentives were provided to respondents for their participation. During introductory instructions to the survey, participants were informed that participation was voluntary; that they could withdraw from the survey at any time, the information they shared would not be linked to them; and that data would be reported in a summarized form only. Respondents were asked if they wished to participate, and

Fig. 3 Map of port zones in grain growing regions of Western Australia, including the main grains produced. White areas indicate non-grain growing regions, and the main grains produced are on an area basis (Harries et al. 2021).

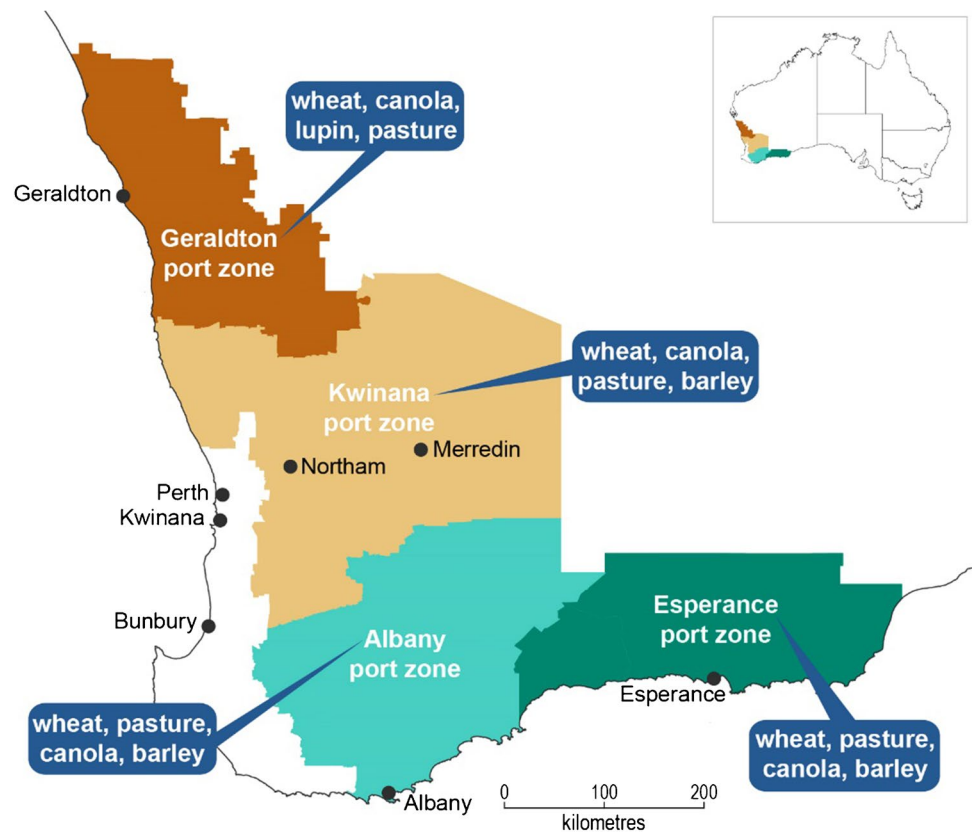


Table 1 Sample stratification by port zone in Western Australia for respondents surveyed in 2020.

Port zone	Annual cropped area (m ha) (source: Grain Industry Association of Western Australia 2014–2019)	Sample stratification sought (%)	Sample stratification achieved (%)	Number of interviews achieved
Albany	1.69	20	31	132
Esperance	1.11	13	11	44
Geraldton	1.61	19	16	69
Kwinana	4.08	48	42	178
Unknown		0	0	2
Total	8.49	100	100	425

affirmative consent was required before the survey could take place. Once all surveys were completed, 10% of survey responses were validated to ensure the survey had been undertaken correctly, and the views of the respondent were fully represented as required by the ISO (ISO 2019). At the completion of the survey, a total of 425 grain-growing businesses had been sampled, representing 11% of the population. To achieve this sample size, 1290 businesses were contacted, resulting in a 33% response rate.

To aid statistical analysis and where possible, closed questions were used to elicit quantitative continuous variables. Where the capture of continuous variables was not considered possible or was deemed to be inappropriate,

answers were categorized with the highest possible level of accuracy. For example, the accuracy with which producers make decisions about nitrogen rates was asked in four levels (<5, 5–10, 10–20, and >20 kg N/ha). Where specific answers were not possible, opinions were elicited using Likert scales with 11 levels (0 to 10) (Bernstein 2005). Participants were given the option to refuse to answer or to indicate that they “did not know” for each question.

2.2 Analysis of results

The questionnaire generated a total of 41 variables relating to respondent demographics and the potential agronomic,

socioeconomic, and logistic factors to which producer's fertilizer decisions are sensitive. An additional variable, "CV of growing season rainfall (GSR)," was calculated using Bureau of Meteorology data for the shire in which the respondent's farm is located (<http://www.bom.gov.au/climate/data/index.shtml>). This variable is the coefficient of variation of GSR (rainfall from April to November) and was calculated by taking the standard deviation of GSR (from 2009 to 2019) and dividing it by the mean from the same period. The list of dependent and significant independent variables used in the statistical analysis is provided in Table 2. A full list of variables and a full report of statistical analysis are provided in the Supplementary Material.

The identification of independent variables used to explain the dependent variables of interest included a combination of agronomic judgement and statistical significance. The models reported in the results section of this paper have retained only those variables which are significant with $p < 0.05$. The software package Stata (StataCorp 2019) was used to conduct these analyses.

Statistical analysis was conducted on decisions required in a fertilizer strategy to determine the agronomic, socioeconomic, and logistical factors that influence these decisions. For the purpose of this study, the key decisions required for a fertilizer strategy are defined as (1) the number of times per year that nitrogen fertilizer is applied to wheat crops,

Table 2 List of variable names, descriptions, and units that are significant in the statistical analyses.

Variable name	Variable description	Unit	Type of variable
Frequency of N application	Number of times per year the respondent applied nitrogen fertilizer to wheat crops, average over the last 3 years	Number	Decision
N rate	Average nitrogen rate for cereal crop	kg N/ha	Decision
N rate accuracy	Accuracy that respondents try to make decisions about nitrogen rates	< 5kg, 5–10, 10–20, >20 kg N/ha	Decision
% liquid	Percentage of nitrogen applied as liquid fertilizer	%	Decision
Time on strategy	Time spent on nitrogen fertilizer strategy	0–10, where 0 is the minimum time and 10 is as long as needed to make sure it is as cost-effective as possible	Decision
Growing season rainfall	Average annual growing season rainfall (April to October)	mm	Agronomic
CV of GSR	Coefficient of variation (CV) of growing season rainfall (GSR) for the shire in each respondent is located (2010–2019)	%	Agronomic
Timeliness before rainfall	The extent the respondent modifies their fertilizer program due to the timeliness of applying nitrogen fertilizer before rainfall events	0–10, where 0 = no modification, 10 = significant modification	Agronomic
Risk of burning crop	That the respondent does not apply too much nitrogen as it can burn the crop	0–10, where 0 is not important and 10 is significantly important	Agronomic
Risk of under fertilizing	That the respondent does not put on too little nitrogen to reduce the risk of missing out on yield benefits	0–10, where 0 is not important and 10 is significantly important	Agronomic
Soil nutrient status	The extent the respondent modifies their fertilizer program due to soil nutrient status determined by soil testing	0–10, where 0 = no modification, 10 = significant modification	Agronomic
Previous legume	The extent the respondent modifies their fertilizer program due to the previous crop or pasture	0–10, where 0 = no modification, 10 = significant modification	Agronomic
% crop	Percentage of arable area cropped each year, average over the last 3 years	%	Logistic
Using all fertilizer	That the respondent uses all purchased fertilizer in a season rather than storing it for the next season	0–10, where 0 is not important and 10 is significantly important	Logistic
Difficulties keeping fertilizer up to machinery	The extent the respondent modifies their fertilizer program due to difficulties keeping fertilizer up to seeding machinery at seeding	0–10, where 0 = no modification, 10 = significant modification	Logistic
Port zone	Port zone	Albany, Esperance, Fremantle, Geraldton, and Kwinana	Regional

(2) the average nitrogen rate applied to cereal crops, (3) the accuracy with which producers apply nitrogen, and (4) the percentage of nitrogen applied as liquid fertilizer. Factors affecting the time spent on developing nitrogen fertilizer strategies were also analyzed.

All economic data are presented in Australian dollars.

3 Results and discussion

3.1 Farm and respondent characteristics

A summary of annual and growing season rainfall, arable farm area, area cropped, and distance to port from the survey is presented in Table 3. Rainfall data reflects the Mediterranean climate that occurs in Western Australia, with the growing season spanning mid-autumn to late spring (April to November), with low rainfall outside of this period. The average annual rainfall was 291 mm, and the growing season rainfall (GSR) was 214 mm. Seventy-eight percent of respondents indicated that the annual average GSR has been decreasing on their farm over the last 20 years. The average arable farm area was 3488 ha, of which an average of 73% was cropped each year. Eighty-three percent of respondents indicated that they managed the farm 10 to 15 years ago. For these respondents, the proportion of the farm cropped has increased by 12% over this period. The uncropped arable area is predominantly used for pasture, with only very small areas of land fallowed. The distance of farms to port ranged from 12 to 450 km, with an average distance of 209 km. The average CV for GSR is 24% which has not changed significantly for respondents over the last 10 to 15 years, although the range has increased. The highest level of CV for GSR was 47%, whereas the highest CV of GSR was 38% 10 to 15 years ago.

Respondents were evenly spread between those with an annual average gross farm income (sum of all receipts from the sale of crops, livestock, and farm-related goods

and services) less than \$1 million/year, between \$1 and 2 million/year, and over \$2 million/year. Respondents were positive about the financial position of their business, with 95% indicating a strong financial position (Likert score > 5). Most respondents indicated they did not plan to sell the farm in the next 3 years (91%), with much smaller proportions indicating they did plan to sell the farm (5%) or would possibly sell the farm (3%) over this period. Just under half of respondents indicated they hoped to purchase land in the next 3 years (40%), with 25% indicating they would possibly purchase and 34% indicating they did not have hopes of purchasing land over this period. Ninety-eight percent of respondents were male. Almost half were between the age of 46 and 60 years, with 30% of respondents younger and 24% of respondents older than this age group. The highest level of education for half of the respondents was upper secondary school (typically 15 to 18 years of age), with 12% of respondents having less education, 33% more education, and 4% preferring not to say.

3.2 Information about nitrogen fertilizer strategies

Respondents applied nitrogen fertilizer between 0 and 5 times each year, averaging 2.2 applications in a season. This has increased from an average of 1.6 applications 10 to 15 years ago. The majority (82%) employ split applications. On average, the respondents applied approximately 36% of their nitrogen as a liquid, ranging between 0 and 100%.

Over the last 10 to 15 years, the average nitrogen rate has increased by 24% from 48 to 60 kg N/ha. Despite over three-quarters of survey respondents experiencing decreasing GSR over the last 10 to 15 years, fertilizer nitrogen rates have increased rather than decreased. The trend towards higher nitrogen application rates over the last 10 to 15 years is attributed to a reduction in the area planted to leguminous crops or pastures (Seymour et al. 2013) and improved water use efficiency (Planfarm BankWest 2019). Improved water use efficiency has been achieved through the adoption of improved agronomy that includes earlier sowing (Fletcher et al. 2016), reduced incidence of soil acidity, amelioration of physical soil constraints (Davies et al. 2019), and adoption of higher-yielding varieties (Trainor et al. 2018).

When considering their fertilizer strategy for the year, 79% of respondents indicated that they try to make decisions about the accuracy of nitrogen applications within 10 kg N/ha. Survey participants were asked how much time they spend on their nitrogen fertilizer strategy on a Likert scale, where 0 is the minimum time, and 10 is as long as needed to make sure it is as cost-effective as possible. The average response was 6.5 (± 1). The average response for 10 to 15 years earlier was 5.3 (± 1), indicating that grain producers have slightly increased the time they spend on their nitrogen fertilizer strategy. Despite fertilizer being,

Table 3 Summary of respondent information regarding rainfall, arable farm area, area cropped, and distance to port for various farming enterprises in Western Australia. Numbers in brackets represent relevant dates and units.

	Mean	Median
Average annual rainfall (2017–2019; mm)	291 (± 8)	280
Average growing season rainfall (2017–2019; mm)	214 (± 7)	200
Arable area (2017–2019; ha)	3488 (± 305)	2400
Area cropped (2017–2019; ha)	2547 (± 252)	1600
Area crop 10 to 15 years ago (if applicable) (ha)	2115 (± 215)	1500
Distance to port (km)	209 (± 9)	200

for many producers, the single biggest variable cost item in their farm budget (AgSurf 2021), this study suggests that producers are not spending significant time on their nitrogen fertilizer strategies. This reflects the flat payoff curve for fertilizer decisions when, in many cases, large deviations from optimal decisions make little difference to profitability (Pannell 2006, 2017).

Respondents indicated they apply most fertilizer during seeding and at the start of tillering, and to a lesser extent at late tillering, as a top-up in August, in March or April, and in the days immediately before seeding. While 78% of respondents indicated that GSR has decreased on their property over the last 20 years, they indicated this declining trend is not having a significant impact on their fertilizer program (average Likert rating 5.5, where 0 is no impact and 10 is significant impact).

Most respondents indicated they have all the data they need to make effective fertilizer decisions, with the most important data sources being soil tests (especially of the topsoil), plant tissue testing, yield mapping, and understanding grain protein levels in the previous crop. However, 19% of respondents indicated they lacked the time or resources to access sufficient data, including soil testing, leaf testing, yield mapping, NDVI/biomass imagery, deeper soil testing, and electromagnetic mapping. Accessing this data is especially important for landholders with larger farms and with a higher level of cropping who have the specific desire to improve their soils' potential for improved production and is likely to become more important as awareness of the benefits of these technologies increase (Robertson et al. 2012; Zhang et al. 2019). Respondents indicated they would like

more accurate seasonal forecasting data, which is likely to remain a major source of uncertainty in the short to medium term. This is a research and development priority so that productivity growth will continue to counteract the negative impacts of rainfall decline (Kingwell and Pannell 2005; Hughes et al. 2017).

3.3 Respondent perceptions of the factors which have the biggest impact on their fertilizer strategy

Respondents were asked to rate the extent to which they modify their fertilizer program due to specific agronomic, socioeconomic, and logistical factors. When asked to indicate the factor with the biggest impact on their fertilizer program, the three dominant factors were rainfall (agronomic), reaching yield targets (agronomic), and budget constraints (socioeconomic) (Fig. 4). Budget constraints (socioeconomic) and soil type (agronomic) were relatively more important 10 to 15 years ago compared with now.

3.4 Statistical analysis of interactions between factors that influence fertilizer strategies

Statistical analysis was conducted on five decision variables. These variables include the number of times nitrogen is applied to wheat within a season, the nitrogen application rate, the accuracy with which respondents determine nitrogen application rates, the proportion of nitrogen fertilizer applied as a liquid, and the time spent on the

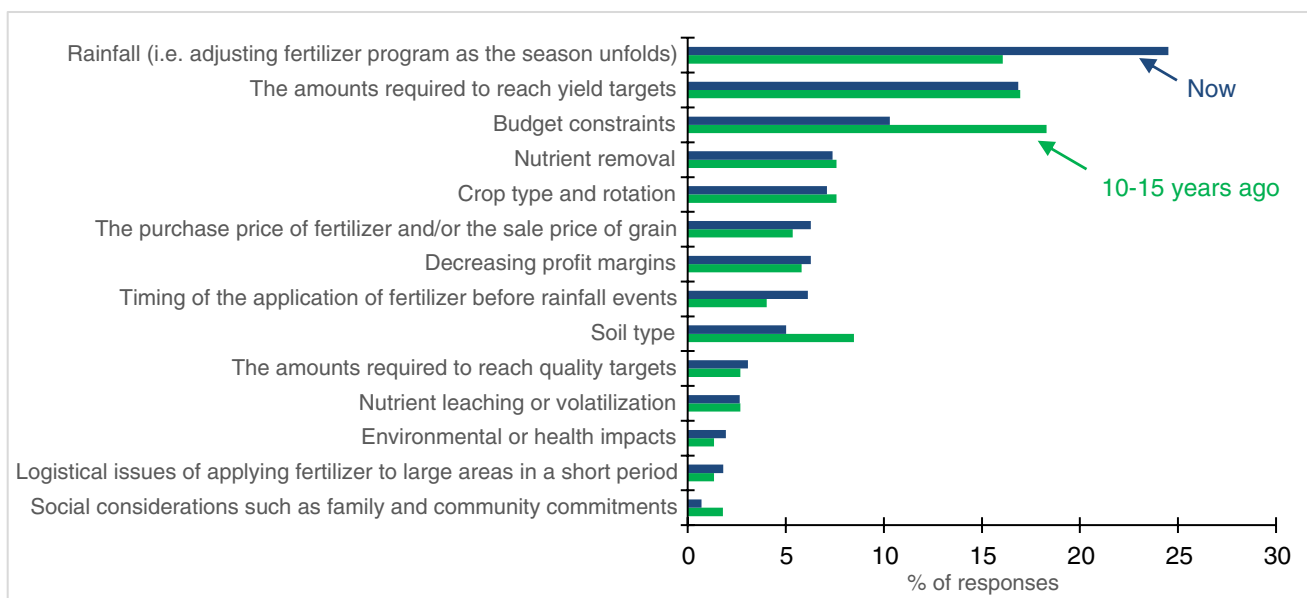


Fig. 4 Factors with the biggest impact on respondents' fertilizer program; 2020 compared with 10 to 15 years previously.

Fig. 5 Drivers influencing each fertilizer decision ranked in order of importance. The majority are agronomic drivers. There are some logistical drivers that are influential (marked with an asterisk). No socioeconomic drivers are statistically significant. Negative influences are listed as (-ve).

Decision	Number of times N is applied	N rate (kg/ha)	Accuracy of N rate	Liquid N used (%)	Time spent developing N strategy
Top drivers	<ol style="list-style-type: none"> 1. Timeliness before rainfall 2. Growing season rainfall (GSR) 3. % liquid* 	<ol style="list-style-type: none"> 1. GSR 2. Variance of GSR (-ve) 3. Timeliness before rainfall 4. Risk of under-fertilising 5. Using all fertiliser* 6. Difficulties keeping fertiliser up to machinery (-ve)* 	<ol style="list-style-type: none"> 1. % liquid (-ve)* 2. Previous legume 3. Port zone 	<ol style="list-style-type: none"> 1. Risk of under fertilising 2. % crop* 3. Difficulties keeping fertiliser up to machinery* 4. Port zone 	<ol style="list-style-type: none"> 1. Soil nutrient status 2. Risk of burning crop 3. Risk of under fertilising 4. % liquid* 5. Previous legume 6. % crop* 7. GSR 8. Timeliness before rainfall

development of their nitrogen strategy. A summary of the statistical analyses is provided in Fig. 5, with the variables that influence each fertilizer decision ranked in order of most to least important. Most factors affecting fertilizer decision are agronomic (factors listed in Fig. 5 that are not underlined), affecting all five decision variables. Logistical factors (factors underlined in Fig. 5) were statistically significant for all decision variables, but there are fewer logistical drivers than agronomic drivers. No socioeconomic drivers were statistically significant for any of the decision variables.

The statistical analyses show that fertilizer decision-making is evolving for grain producers in Western Australia in the context of climate and market uncertainty. Agronomic factors were the dominant influence on fertilizer decisions for the period covered by the survey, logistical issues are growing, and socioeconomic issues had less influence. These findings have implications worldwide for grain production in dryland cropping systems. Global grain production is increasing on decreasing areas of land, putting pressure on the imperative to make efficient fertilizer decision. We recommend that private and public investment in research, development, extension, and adoption activities be focused on agronomic issues. Seasonal forecasting is a research and development priority so that productivity growth will continue to counteract the negative impacts of climate change. Little research through to adoption activities is given globally to logistical issues of fertilizer use, yet they are increasing in importance with the global trend of increasing yields, crop nutrient requirements, and fertilizer application. Logistic issues, such as improving planning, organizational, and technical capacity for developing and implementing fertilizer strategies, should be given stronger priority for investment in agricultural research, development, extension, and adoption activities.

Since the survey was conducted, the ratio of nitrogen fertilizer to grain price has spiked (Ellis 2022; Pannell 2021) making fertilizer decision even more critical for producers globally. Historically, these spikes have been short-term. The results from our survey reflect growers' decisions in a relatively stable economic environment, and under these conditions, agronomic and logistical issues are the most pressing factors to be addressed through the extension of research.

4 Conclusion

Results of this study show for the first time that, while grain producers are making nitrogen fertilizer decisions to maximize profit, the factors to which these decisions are most sensitive are currently agronomic, rather than socioeconomic or logistic. In dryland cropping systems, yield is closely linked to rainfall and factors that affect the availability of soil water to crops, such as soil texture.

Logistic factors are a growing influence on fertilizer decisions. Where farm size and cropping areas are increasing, producers are experiencing difficulties keeping fertilizer up to machinery at seeding, and this is likely to be restricting fertilizer rates that can be applied in this operation.

The likely contributing factors to the decreasing sensitivity of nitrogen decisions to socioeconomic factors include the flat payoff function to nitrogen fertilizer application. This flat payoff function often allows wide flexibility in profit-maximizing decisions about nitrogen fertilizer rates. Another contributing factor is the trend in the ratio of fertilizer to grain prices which has plateaued since 2005 (although it has experienced spikes in 2008 and 2021/22).

Environmental factors had little influence on fertilizer decision-making in our study which is attributed to low fertilizer N rates in Australia by international standards due

to low nitrogen demand by dryland crops and the lack of subsidies on crops or fertilizers that promote overuse.

Addressing agronomic and logistical issues is required to ensure sustainable development of global grain production in the context of continued climate change and growing volatility in global fertilizer and grain markets. Future fertilizer research, development, extension, and adoption activities could focus on issues such as the accuracy of seasonal forecasting and improving the planning, organizational, and technical capacity of farmers in developing fertilizer strategies.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13593-023-00867-y>.

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Authors' contributions All authors contributed to the study's conception and design. Data collection was conducted by *Thinkfield* supervised by *Research Solutions*. Statistical analyses were conducted by Michael Burton. The first draft of the manuscript was written by Elizabeth Petersen, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated during the current study are not publicly available as confidentiality was promised to survey participants.

Code availability The code used in the statistical analyses is available from the corresponding author on reasonable request.

Declarations

Ethics approval Approval was provided by the University of Western Australia Human Ethics to conduct the survey.

Consent to participate Verbal informed consent was obtained prior to each of the phone interviews.

Consent for publication As individual results are not presented in the paper, this declaration is not applicable.

Conflict of interest The authors declare no competing interests.

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