
# Optimizing Chloride (Cl) Application for Enhanced Agricultural Yield

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***Abstract.***

*The optimization of chloride ($Cl^-$) application rates is crucial for enhancing crop yields and reducing environmental impact in agricultural systems. This study investigates the relationship between chloride application rates and wheat yields, focusing on Club wheat cultivation in a 19.76-hectare field in Washington State. The target yield was set at 3765 kilograms per hectare, with seeding conducted at 67.24 kilograms per hectare using conservation tillage practices. Potassium chloride was applied at rates of 0, 14, 27, and 41 kilograms per hectare to determine the most effective chloride levels for varying field conditions. Rigorous data processing and analysis methods were employed to ensure quality and accuracy. Exploratory analysis revealed yield variations from 3080.6 kg/ha to 4733.6 kg/ha and chloride application rates from 4 kg/ha to 40.8 kg/ha. Weak correlations were observed between yield, chloride application rate, and slope, with the highest correlation between yield and slope (0.26). The optimal agronomic rate of chloride was identified at 40.8 kg/ha, maximizing yield response. However, the economic optimum rate was significantly lower at 4 kg/ha, due to the high cost of chloride fertilizer relative to the return from increased wheat yield. The Generalized Additive Model (GAM) analysis indicated that slope had a marginally significant impact on yield (p = 0.0479), while soil-related variables (clay, silt, sand, water storage) did not significantly influence the model (p = 0.9011). Random Forest (RF) analysis was conducted to enhance predictive accuracy, using a dataset with 60 samples and 6 predictor variables, and evaluated through 10-fold cross-validation. The model with an mtry value of 2 was considered most suitable, explaining approximately 23.82% of the variation in yield, with an RMSE of 362.6793 and an MAE of 310.4855. While RF demonstrated superior predictive capability compared to GAM, both models suggest the need for additional relevant variables to improve yield variability explanation. This study underscores the importance of considering economic factors in determining agricultural input application rates, highlighting the significant discrepancy between agronomic and economic optimal rates. The findings emphasize the necessity of an integrated approach that includes both agronomic and economic aspects for optimizing agricultural production and sustainability. Precision in chloride application is crucial for yield enhancement and minimizing environmental impacts, thereby promoting sustainable agricultural* *practices.*

***Keywords.***
*chloride rate, yield, precision agriculture, data analysis, on-farm research.*

## 1 Introduction

In the context of global agricultural challenges, wheat cultivation remains pivotal in addressing the escalating demand for food necessitated by the burgeoning world population. Given its remarkable production trajectory, wheat has solidified its position as the second-largest staple food worldwide. Despite this prominence, the significance of Chloride ($Cl^{-}$) as a plant nutrient remained relatively overlooked until recent years, owing to the prevailing high soil $Cl^{-}$ levels and sufficient rainfall inputs that historically met crop demands (Large, 1954).

However, the mobile nature of Cl in soil renders them susceptible to leaching, precipitating deficiencies particularly in scenarios characterized by high-yield production in deep, sandy soils with limited organic matter and abundant rainfall, or in soils rich in potassium (K) (LaRuffa, 1999). As such, the utilization of $Cl^{-}$ in wheat cultivation has garnered increased attention, with a growing emphasis on their synergistic effects with nitrogen (N) in optimizing crop productivity. Notably, foliar applications of $Cl^{-}$ have emerged as potential strategies to enhance wheat yield and total N, especially in sandy soils where deficiencies are prevalent.

To elucidate the efficacy of $Cl^{-}$ applications, winter wheat studies were conducted over three site-years, evaluating the impact of foliar $Cl^{-}$ applications on grain yield and grain N levels. Despite the critical role of $Cl^{-}$ as essential plant nutrients (Johnson et al., 2003), their influence on yield and protein content remains a subject of inquiry. Moreover, the multifaceted functions of $Cl^{-}$, encompassing water regulation, disease suppression, and nitrification inhibition, underscore its indispensable role in plant physiology and crop management (Thomason et al., 2001; Christensen et al., 1985).

Additionally, $Cl^{-}$ has been recognized for its pivotal involvement in various physiological processes, including photosynthesis, enzyme activation, and nutrient transport, further accentuating its significance in crop nutrition and health (Engel et al., 1994; Freeman et al., 2006; Christensen et al., 1981; Díaz-Zorita et al., 2004; Lamond et al., 1999; Li et al., 2017). Furthermore, empirical evidence suggests Cl's efficacy in disease suppression and yield enhancement, indicating its potential as a valuable component in crop management strategies (Richard et al., 1994; Fixen, 1986).

Despite the promising outcomes observed in response to $Cl^{-}$ fertilization, the widespread promotion of these nutrients often overlooks soil test levels, necessitating a comprehensive evaluation of their application effects. The objective of this study is to investigate and characterize the optimal application rates of chloride in an agricultural field, focusing on two main aspects: determining the average agronomical optimal rate and the average economic optimal rate in the field. The analysis aims to provide detailed insights that can contribute to more efficient chloride application, promoting sustainability and profitability in agriculture.

## 2 Materials and Methods

The study area, situated in Washington State, was selected as the focal point for investigating the optimal chloride application rates for Club wheat cultivation within a 19.76-hectare parcel of land. The target yield was set at approximately 3,765 kilograms per hectare. To initiate the research, seeding was performed at a rate of approximately 67.24 kilograms per hectare in October 2021, employing conservation tillage practices.

Liquid potassium chloride (KCl) was incorporated into the study as the chloride source. Application rates of 0, 14, 27, and 41 kg per hectare were utilized to explore a range of chloride rates. This approach aimed to identify the most efficient chloride rates customized to the distinct field characteristics observed within the study area.

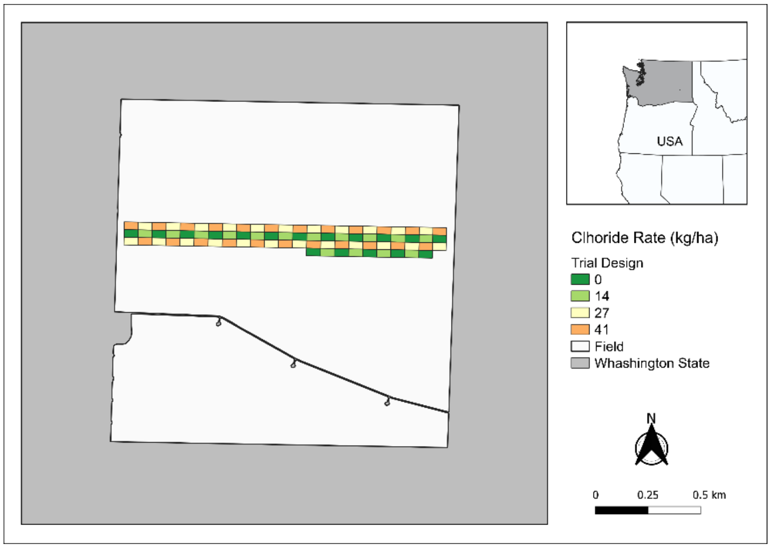



**Figura 1 – Illustration the spatial distribution of Chloride Rates in the Field**

Data processing followed a rigorous methodology to ensure quality and accuracy. Initially, field edge areas (headlands and lateral edges) were removed due to their unique conditions and high uncertainty in yield data. Outliers were identified and eliminated, defined as points with yield or application rates beyond four standard deviations from the field mean or where harvester speed was above 13.2 km/h or below 1.1 km/h. Yield polygons were created around each remaining data point, adjusted for harvester width and point spacing. Polygons with less than 95% or more than 110% coverage by input polygons were removed. The deviation of the area-weighted input rate was calculated for each polygon, and those with high deviations were discarded. Similar consecutive polygons were grouped and subdivided into observational units for homogeneity.

Data were aggregated using area-weighted averages, including yield, application rates, and non-experimental variables such as topography and soil characteristics. These procedures were based on existing literature and experience since 2016 in the design and processing of On-Farm Precision Experiment (OFPE) data, as referenced in Lara et al. (2023) and Hegedus, Maxwell, and Mieno (2022). This meticulous processing ensured the integrity and reliability of the data used to identify optimal chloride application rates in the studied agricultural field. This data processing approach addresses specific challenges inherent to OFPE, including dealing with measurement errors and ensuring accurate aggregation of spatial data points into meaningful units for analysis.

## Data analysis methods for Agronomical Optimum Rate and Economic Optimum Rate

The data analysis aimed to identify both the agronomical optimum rate and the economic optimum rate of chloride application, utilizing advanced statistical and machine learning methods to ensure robust and accurate findings. The dataset was prepared by renaming key variables for clarity, ensuring columns such as yield, chloride application rate, slope, and soil properties were correctly labeled. Data types were verified, and any missing values in critical columns were removed to maintain a clean dataset for analysis. Exploratory Data Analysis (EDA) was conducted to understand the distribution and correlation of key variables. Histograms were plotted to visualize the distribution of yield and chloride application rates. Additionally, a correlation matrix was generated to examine the relationships between yield, chloride application rate, and slope.

To identify the agronomical optimum rate of chloride application, a Generalized Additive Model (GAM) was employed. This model used yield as the dependent variable, with chloride application rate and slope as explanatory variables. Smoothing splines were applied to account for non-linear relationships. The agronomical optimum rate was determined by finding the point on the response curve where yield was maximized. This involved generating a sequence of chloride application rates, predicting the yield for each, and identifying the rate corresponding to the maximum predicted yield.

To calculate the economic optimum rate of chloride application, a similar approach using GAM was employed. This model used the same explanatory variables—chloride application rate and slope—but the optimization considered economic parameters. Specifically, the model incorporated the cost of fertilizer and the market price of wheat to form a profit function. The economic optimum rate was identified by maximizing this profit function, which involves finding the chloride application rate that provides the highest profit. To evaluate the influence of soil properties and slope on yield, a GAM was employed. This model included variables such as clay content, silt content, sand content, and water storage, alongside chloride application rate and slope. This approach helps to capture non-linear relationships and interactions between variables, providing a comprehensive understanding of the impact of these factors on yield.

Machine learning, specifically Random Forest (RF), was used to further enhance predictive accuracy and robustness. While GAM is effective in capturing non-linear relationships and interactions, Random Forest can handle complex interactions and non-linearities more flexibly. The reason for conducting machine learning analysis after using GAM is to leverage the strengths of both modeling approaches. GAM provides a robust framework for understanding the non-linear relationships and interactions between variables, while Random Forest offers flexibility and robustness in handling complex datasets and interactions that may not be fully captured by GAM. By applying both techniques, the analysis ensures comprehensive and reliable results, providing a deeper understanding of the factors influencing yield and the optimal application rates.This comprehensive approach ensures that the analyses are robust and adequate for identifying optimal chloride application rates, while also assessing the impact of environmental and input variables on agricultural productivity (Chlingaryan, Sukkarieh and Whelan, 2018).

## 3 Results and Discussion

The yield data, chloride application rate, and slope were analyzed to determine the relationships between these variables. Exploratory analysis revealed significant variations in yield values, ranging from 3080.6 kg/ha to 4733.6 kg/ha, and in chloride application rates, which varied between 4 kg/ha and 40.8 kg/ha. The correlation matrix indicated weak correlations between yield, chloride application rate, and slope, with the highest correlation observed between yield and slope (0.26).

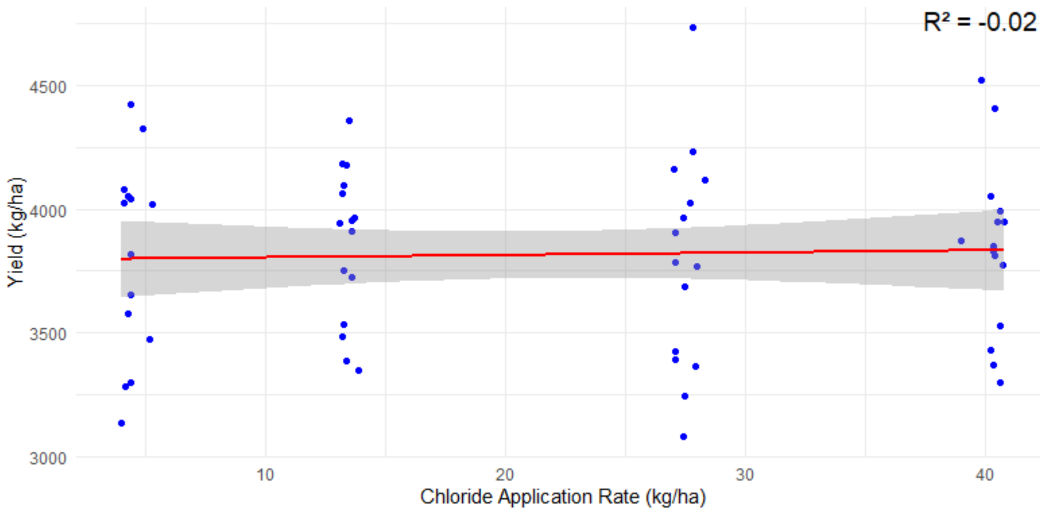
The optimal agronomic rate of chloride was determined to be 40.8 kg/ha, where yield response was maximized. However, when considering economic parameters (fertilizer price = $0.28/kg and wheat price = $0.46/kg), the optimal economic rate was calculated to be 4 kg/ha. This significant discrepancy can be attributed to the non-significant impact of chloride on yield ($p = 0.9011$), suggesting that increases in chloride application do not result in proportional increases in yield. The yield response curve to chloride was relatively flat, indicating limited efficacy of additional chloride application. The analysis of the optimal economic rate is substantially lower due to the high cost of chloride compared to the return obtained from increased wheat yield. The cost of chloride ($0.28/kg) is relatively high, while the sale price of wheat ($0.46/kg) does not offset the additional cost of high-dose chloride application.

The analysis of soil and slope influence on productivity was conducted using a Generalized Additive Model (GAM) with adjusted degrees of freedom. The results indicated that slope had a marginally significant impact on yield with a p-value of 0.0479. In contrast, soil-related variables, including clay, silt, sand, and water storage, did not present sufficient variability to significantly influence the model ($p = 0.9011$). The GAM was employed to identify the agronomic threshold of chloride and assess its effects on yield. The parametric coefficient for the intercept was estimated at 3814.61 (Standard Error: 47.16), with a highly significant p-value ($p < 2e-16$). Analysis of the smoothed terms revealed that the chloride application rate did not have a significant impact on yield (EDF = 1, Ref.df = 1, F = 0.016, $p = 0.9011$). On the other hand, slope was shown to be a significant factor (EDF = 1, Ref.df = 1, F = 4.088, $p = 0.0479$). The model presented an adjusted R-squared of 0.0354 and explained 6.81% of the deviance, indicating that it explains only a small portion of the variation in yield. These results suggest that slope has a significant effect on yield, while the chloride application rate does not show a significant relationship.

The practical implication of these findings is significant for guiding agricultural practices. Terrain slope should be considered an important factor in agricultural management to optimize crop productivity. However, the small proportion of variation explained by the model also indicates that other factors not included in the analysis may have a substantial influence on yield. Future studies should consider including other relevant variables and collecting additional data to improve the predictive capacity of models and offer more comprehensive recommendations for agricultural management. Precision in chloride application is emphasized not only for yield enhancement but also for minimizing environmental impacts. Over-application of fertilizers can lead to nutrient leaching and runoff, contributing to environmental degradation. Therefore, precision agriculture techniques are crucial in balancing agronomic needs with environmental stewardship. By optimizing chloride application rates, farmers can improve yields while reducing the negative environmental impacts associated with improper fertilizer use (Graham et al., 2017).

The analysis of chloride application influence on productivity was visualized through a scatter plot (Figure 2), complemented by a smoothing line obtained through a Generalized Additive Model (GAM). The scatter points represent individual observations, where each point reflects productivity relative to the amount of chloride applied. The GAM smoothing line was fitted to capture potential nonlinear relationships between these variables. The smoothing line in the graph does not show a pronounced trend, suggesting a lack of clear relationship between productivity and chloride applications. This observation is reinforced by the adjusted R-squared value, which is only 0.02. This value indicates that the model explains only 2% of the variation in productivity, suggesting that chloride applications do not significantly contribute to the observed variability in crop productivity.

**Figure 2 – Yield response to Chloride Applications**




The results confirm that chloride application does not have a significant relationship with productivity, as evidenced by the low proportion of variation explained by the model. The statistical insignificance of the relationship, along with an adjusted R-squared value of 0.02, suggests that other factors not included in the model may be more determinant in agricultural productivity. These findings highlight the need for a more comprehensive approach that considers multiple variables and environmental factors to fully understand the determinants of productivity in agricultural practices. Although reports have shown that $Cl^-$ fertilization improves grain yields in $Cl^-$ deficient soil (Graham et al., 2017; Freeman et al., 2006; Christensen et al., 1981; Díaz-Zorita et al., 2004; Lamond et al., 1999; Engel et al., 1994), the effect of $Cl^-$ supply on the performance of plants grown under conditions of $Cl^-$ sufficiency is poorly understood. Studies have demonstrated some positive effects of $Cl^-$ supply on plant growth (Xu et al., 2013; Ibrahim et al., 2016).

The Random Forest analysis was conducted on a dataset containing 60 samples and 6 predictor variables, without any data preprocessing steps. To evaluate the model's performance, cross-validation with 10 folds was used. The mtry parameter in the Random Forest model represents the number of predictor variables considered at each split of the tree node. This parameter is tuned to find the best model performance. The results for different mtry values are presented in Table 1.

**Table 1: Performance of the Random Forest Model for Different mtry Values**

| mtry | RMSE | $R^2$ | MAE |
|---|---|---|---|
| 2 | 362.6793 | 0.2382457 | 310.4855 |
| 4 | 384.3324 | 0.2006709 | 332.1444 |
| 6 | 410.2130 | 0.2022376 | 354.2871 |

The model with an mtry value of 2 was considered the most suitable, as it presented the lowest RMSE value. This model explained approximately 23.82% of the variation in the response variable, with an RMSE of 362.6793 and an MAE of 310.4855. Although the

$R^2$ value indicates a modest predictive capability, the results suggest that including more variables or applying preprocessing techniques could improve the model's explanatory power. The Random Forest model demonstrated a slightly superior predictive capability compared to the GAM, explaining a larger proportion of the variation in the response variable and offering better performance metrics. However, both models indicate that there is room for improvement in explaining yield variability, suggesting the need to include more relevant variables.

## Conclusion

This study highlights the importance of considering economic factors in determining agricultural input application rates, emphasizing the significant difference between agronomic (40.8 kg/ha) and economic (4 kg/ha) rates. The yield response curve to chloride, as modeled by the Generalized Additive Model (GAM), does not show a significant increase in yield for higher chloride rates, implying that adding more chloride does not result in a proportional increase in yield. Consequently, the economically optimal chloride application rate is very low. The analysis revealed that chloride application did not have a significant impact on wheat yield, and the effectiveness of additional chloride application was limited. Slope had a marginally significant impact on yield ($p = 0.0479$), while the soil variables analyzed did not significantly influence the model. The low explanatory power of the model suggests that future studies should consider including more variables that influence agricultural yield. This study provides a comprehensive insight into chloride application and its impacts on wheat yield, highlighting the need for an integrated approach that considers both agronomic and economic aspects for optimizing agricultural production.

## References

Chlingaryan, A., Sukkarieh, S. and Whelan, B., 2018. Machine learning approaches for crop yield prediction and nitrogen status estimation in precision agriculture: A review. Computers and electronics in agriculture, 151, pp.61-69.

Christensen, N.W., and B. Marcia. 1985. Chloride and liming effects on soil Nitrogen form and take-all of wheat. Agron. J. 77: 157-163

Christensen NW, Taylor RG, Jackson TL, Mitchell BL 1981: Chloride effects on water potentials and yield of winter wheat infected with take-all root rot. Agronomy Journal. 73(6), 1053–1058. doi:10.2134/agronj1981.00021962007300060035x.

Díaz-Zorita M, Duarte GA, Barraco M 2004: Effects of chloride fertilization on wheat (Triticum aestivum L.) productivity in the Sandy Pampas Region, Argentina. Agronomy Journal. 96(3), 839–844. doi:10.2134/agronj2004.0839.

Engel RE, Eckhoff J, Berg RK 1994: Grain yield, kernel weight, and disease responses of winter wheat cultivars to chloride fertilization. Agronomy Journal. 86(5), 891–896. doi:10.2134/agronj1994.00021962008600050025x.

Freeman KW, Girma K, Mosali J, Teal RK, Martin KL, Raun WR 2006: Response of winter wheat to chloride fertilization in sandy loam soils. Communications in Soil Science and Plant Analysis. 37(1314), 1947–1955. doi:10.1080/00103620600767231

Graham C, Woodard H, Bly A, Fixen P, Gelderman R 2017: Chloride fertilizers increase spring wheat yields in the Northern Great Plains. Agronomy Journal. 109(1), 327–334.

doi:10.2134/agronj2016.04.0205.

Hegedus, Paul B., Bruce D. Maxwell, and Taro Mieno. 2022. “Assessing Performance of Empirical Models for Forecasting Crop Responses to Variable Fertilizer Rates Using on-Farm Precision Experimentation.” Precision Agriculture 24 (2): 677–704. https://doi.org/10.1007/s11119-022-09968-2.

Ibrahim MFM, Faisal A, Shehata SA 2016: Calcium chloride alleviates water stress in sunflower plants through modifying some physio-biochemical parameters. American-Eurasian J. Agric. & Environ. Sci. 16(4), 677–693.

Johnson, G.V., and H. Zhang. 2003. Sulfur requirements of Oklahoma crops. Division of Agricultural Sciences and Natural Resources, Oklahoma State University, 2003.

Lamond RE, Roberson DD, Rector K 1999: Chloride fertilization bumps wheat yields, profits. Fluid Journal. 7(27), 14–15.

Lara, Alfonso de, Taro Mieno, Joe D. Luck, and Laila A. Puntel. 2023. “Predicting Site-Specific Economic Optimal Nitrogen Rate Using Machine Learning Methods and on-Farm Precision Experimentation.” Precision Agriculture 24 (5): 1792–812. https://doi.org/10.1007/s11119-023-10018-8.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

LaRuffa, J. M., G.V. Johnson, S.B. Philips, and W.R. Raun. 1999. Sulfur and chloride response in Oklahoma winter wheat. Better Crops 32.4: 28-30.

Thomason, W.E., K. J. Wynn, K. W. Freeman, E. V. Lukina, R. W. Mullen, G. V. Johnson, R. L. Westerman, and W. R. Raun. 2001 Effect of chloride fertilizers and lime on wheat grain yield and take-all disease. J. Plant Nutr. 24: 683-692.

Xu C, Xuemei L, Zhang L 2013: The effect of calcium chloride on growth, photosynthesis, and antioxidant responses of Zoysia japonica under drought conditions. PloS One. 8(7), e68214. doi:10.1371/journal.pone.0068214.