Turkish Journal of Range and Forage Science, 2025, 6(2): 85-100
doi: 10.51801/turkjrfs.1765045

Research

Turkish Journal of Range and Forage Science
https://dergipark.org.tr/tr/pub/turkjrfs

Determining Economically Optimal Fertiliser Doses in Eastern Anatolian Natural Rangelands: A Fertilisation Study Data Revisited

Abdurrahman KARA[1]

[1]Dicle University, Faculty of Agriculture, Sur, Diyarbakır, Türkiye

A R T I C L E I N F O

Received *15/08/2025*
Accepted *26/10/2025*

Keywords:
Economic analysis,
nitrogen and phosphorus,
rangeland fertilisation,
partial budget,
pooled regression,
rangeland condition,
surrogate market

A B S T R A C T

This study aimed to identify economically optimal nitrogen and phosphorus rates along with examining their synergistic effects and climate variables in Eastern Anatolia's natural rangelands. Using data from a prior fertilisation trial, pooled regression models, descriptive statistics, and partial budget analysis were employed. Results indicated that nitrogen had a limited standalone impact but showed synergistic benefits when combined with phosphorus in moderate-to-good condition rangelands. While moderate-condition rangeland exhibited notable improvements, these were not statistically significant compared to poor-condition rangeland. Good-condition rangelands responded weakly to fertilisation, suggesting inherent productivity limits marginal gains. Economic analysis confirmed diminishing returns at higher input levels, supporting lower fertiliser rates in moderate rangeland. Optimal doses were determined as 90 kg·ha^{-1} nitrogen and 40 kg·ha^{-1} phosphorus for poor-condition rangelands, and 30 kg·ha^{-1} nitrogen with 40 kg·ha^{-1} phosphorus for moderate and good rangeland sites.

Results also revealed that seasonal humidity, although only marginally significant, had a more pronounced effect than temperature or precipitation, highlighting its potential role as a moderating climatic variable in fertilisation outcomes. The study concludes that rangeland fertilisation strategies should be site-specific, balancing ecological context with economic feasibility. Prioritising poor-condition degraded rangelands may offer long-term restoration benefits, not necessarily for immediate economic returns, but for their potential in enhancing productivity recovery and ecological restoration towards historical benchmarks. Achieving resilient agricultural landscapes and sustainable outcomes requires adaptive fertilisation practices and continuous monitoring.

s

1. Introduction

Natural rangelands play a pivotal role in the sustainability of low-input livestock production systems, not only by providing free forage to farm animals, but also by generating invaluable ecosystem services such as biodiversity conservation, soil fertility, water quality regulation, pollination, and carbon cycling, outputs that are neither quantifiable nor monetarily measurable (Williams et al., 1968; Altın et al., 2005). Although rangelands yield comparatively modest agricultural value, their vast geographic coverage renders them economically and socially significant (Schacht & Reece, 2009). Consequently, low-input, pasture-based livestock production has served for centuries

*Corresponding Author: abdurrahman.kara@dicle.edu.tr

as a vital source of livelihood and cultural identity in numerous regions worldwide (Williams et al., 1968; Gintzburger et al., 2006; Pardini, 2009). In particular, in semi-arid and arid regions, the sustainability of both quantity and quality of natural forage resources, key inputs for livestock production, is directly associated with rangeland productivity.

According to the latest FAO dataset (2023), approximately 45% of the global terrestrial land area and 51% of Türkiye's land area are classified as rangeland, encompassing grasslands, shrublands, and barren lands. However, the Turkish Statistical Institute reports that the area of permanent pasture and meadows is 14,617 million ha (TURKSTAT, 2024a), of which 13,270 million ha is permanent natural pastures (Anonymous, 2025a), constituting around 17% of the total land asset of the country.

The discrepancy between the two sources concerning Türkiye's rangeland resources stems from differences in the land classification methodologies employed. While the FAO's assessment relies on NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) technology, Türkiye's estimations are based on cadastral surveys conducted at the settlement level under Law No. 4342 on Pastures, with registered areas taken into account. Moreover, in addition to the officially recognised meadow and pasture lands, approximately 16.1 million hectares of land—classified under 'other' and deemed unsuitable for the cultivation of crop species—are also utilised for grazing purposes (Gökkuş, 2018). When these areas are included, the proportion of grazing land may reach approximately 40% of the total land area of the country.

Based on the data from 2024, it has been estimated that there are approximately 17.25 million livestock units in Türkiye, of which about six million are composed of purebred cattle (TÜRKSTAT 2024b). Since pure breeds are not suitable for pasture-based livestock farming (Kara, 2019), considering the remaining 11.3 million livestock units, it is noted that there is approximately 1.2 hectares of pastureland per livestock unit in Türkiye. This amount was recorded as 4.3 hectares in the 1940s (Balabanlı et al., 2009).

The shrinking in pasture area per animal unit (AU) is not solely due to an increase in the number of animals, but rather the reclassification of existing pasture areas through legal and administrative regulations. Following the enactment of the Land Distribution Law for Farmers in 1945, some of these areas were converted to agricultural land; others were designated as forest land with the establishment of the Ministry of Forestry in 1969, while the rest were reclassified into different land use categories in the following years (Gökkuş, 2018). The decrease in pasture availability, combined with an increase in livestock numbers, has approximately quadrupled the grazing pressure on pastures (from 4.3 ha AU^{-1} to 1.2 ha AU^{-1}). This issue is not unique to Türkiye; similar problems are, of course, observed worldwide. Pastures are increasingly deteriorating and losing their productive potential due to factors such as climate change and associated droughts, population growth, irregular grazing, agricultural industrialisation, and rising land demand (Cowie et al., 2019; di Virgilio et al., 2019; Holechek et al., 2020).

In a study covering most of Türkiye's pastures (Avağ et al., 2012), it was concluded that only approximately 12.4% are in good or very good condition, capable of producing sufficient and high-quality feed for animals, while the remaining 87.6% are in moderate or poor condition. Considering the impact of the destruction of vegetation, it is reported that the losses in production and forage quality of pastures in Türkiye are due to overgrazing and, even more so, untimely grazing (Gökkuş, 2018).

One of the most important reasons for this is related to the legal status of the pastures. Rangelands in Türkiye constitute public property administered and regulated by the state. Under Law No. 4342 on Pastures, applicable in Türkiye, the right to use the rangeland is given to one or more villages or municipalities. They may be leased to individuals engaged in or intending to pursue animal husbandry, contingent upon the implementation of state-approved rangeland improvement measures, for a maximum period of twenty-five years (Anonymous, 1998).

The communal use of pastures in Türkiye leads to opportunistic grazing as soon as the snow melts, and it continues without necessary maintenance and improvement until the snow falls again. In regions with no snowfall and no snow cover, grazing is possible year-round, provided the weather is not rainy. This situation constitutes the most significant dilemma for pasture-based livestock farming in Türkiye (Gökkuş, 2018).

It is reported that the earliest recorded pasture improvement efforts aimed at enhancing the declining forage quality of pastures due to overgrazing, soil erosion, and increasing livestock activities began in the late 19th and early 20th centuries, particularly in the United States (Staub et al. 2016).

One of the earliest examples of efforts to increase productivity in pastures through fertilisation is the pasture fertilisation study conducted in the fall of 1969 in North Dakota, which investigated the effects of nitrogen and phosphorus fertilisers on forage yield and species composition (NDSU, 1970).

Pasture improvement efforts in Türkiye gained momentum, especially after the enactment of the Pasture Law. Between 2000 and 2025, the Ministry of Agriculture and Forestry carried out a total of 3,162 pasture improvement projects covering a total of 2,461,939 hectares of pastureland, most of which have been completed (Anonymous, 2025a). The area covered by these pasture improvement projects constitutes approximately one-fifth (18.6%) of the total pasture area.

In pasture improvement efforts, various activities such as weed control, construction of water troughs, scratching posts and shades for animals, grazing management, training, and fertilisation are considered. Among these, fertilisation expenses constitute a significant budget item, accounting for approximately 25% of the total budget and 40% of the budget allocated specifically for improvement, according to official records (Anonymous, 2025b).

It is reported that although the distribution is not uniform, the soils in Türkiye are generally rich in potassium but poor in nitrogen (N) and phosphorus (P) (Eyüpoğlu, 1999). The 2024 TURKSTAT data on fertiliser use in Türkiye reflects this situation, with 66.4% of the total 13.75 million tons of fertilisers being nitrogen-based, 31.3% phosphorus-based, and only 2.3% potassium-based (TURKSTAT, 2024c).

To date, numerous valuable studies have been conducted on fertilisation in pastures in Türkiye. However, these studies have generally focused on the effects of nitrogen and phosphorus fertilisation on forage yield and botanical composition. Additionally, a significant portion of these studies spans two years and typically represents studies conducted in pastures with a single pasture condition class. The relationship between climate parameters and forage yield has not been examined in these works. Furthermore, economic analysis has been out of the scope in most of these studies (Koç et al., 2003a; Koç & Gökkuş. 2000; Demirel & Türk, 2017; Uslu et al. 2021; Kılıç & Çınar, 2021; Altın et al. 2010; Gürel, 2023). Excluding Algan et al. (2018), in the few studies that have used economic concepts such as economic optimum or net profit (Polat et al. 2007; Aydın & Uzun, 2005), the methods of these calculations have not been addressed.

It is evident that longer-term studies considering different pasture condition classes are needed to observe the cumulative effects of fertilisation over time, given that plant species respond differently to nutrients (Delalandre et al., 2025; Li et al., 2024) and pastures are classified into different condition classes based on their plant composition (Koç et al., 2003b). Unlike previous research, this study aims to determine the economically optimal nitrogen and phosphorus doses by adopting a more comprehensive approach integrating different pasture condition classes, economic analysis, and climate parameters such as precipitation and relative humidity over a broader timescale. Building on the fertilisation trials conducted by Mermer et al. (1996) in pastures with poor, moderate, and good conditions, the goal is to provide a scientific basis for economic and sustainable fertilisation strategies to enhance pasture productivity.

2. Materials and Methods

Study Data

The data utilised in this study were derived from the research conducted by Mermer et al. (1996), aimed at enhancing the productive capacity of natural rangelands in Eastern Anatolia and establishing a sustainable system. In this prior study, nitrogen and phosphorus fertilisers were applied to rangelands previously classified as poor, moderate, and good in condition. The research area encompasses the rural neighbourhoods of Güzelyurt and Başaklı in the Palandöken and Oltu districts of Erzurum Province, respectively, along with the Kırkpınar rural neighbourhood in the Erciş district of Van Province.

In their study, Mermer et al. (1996) posited that rangelands with vegetation coverage exceeding 30% could be enhanced through fertilisation. Consequently, they classified village rangelands into three categories, i.e. poor, moderate, and good condition, based on vegetation cover and productivity criteria. For instance, rangelands

yielding less than 800 kg ha^{-1}, dominated by grazing-resistant species such as *Festuca ovina* due to intensive overgrazing, were classified as poor. Those with yields between 800–1000 kg ha^{-1} and a reasonable presence of legumes in the botanical composition were defined as moderate. Rangelands exhibiting high legume content, desirable species composition, and productivity exceeding 1000 kg ha^{-1} were categorised as good.

Accordingly, the selected study sites included the Güzelyurt rural neighbourhood (Palandöken district, Erzurum Province), representing poor-condition rangeland due to its proximity to settlements and consequent grazing pressure; the Kırkpınar rural neighbourhood (Erciş district, Van Province), representing moderate-condition rangeland based on its distance from the village and moderate slope; and the Başaklı rural neighbourhood (Oltu district, Erzurum Province), representing good-condition rangeland characterised by its elevation and relatively undisturbed vegetation structure.

Researchers conducted their study between 1990 and 1992, employing a factorial arrangement within a Randomised Block Design, with four fixed replications. The experimental treatments consisted of four nitrogen doses (0, 30, 60, and 90 kg ha^{-1}) and three phosphorus doses (0, 40, and 80 kg ha^{-1}), resulting in twelve distinct fertiliser combinations. Fertilisers were applied annually in the spring after snowmelt. Each plot measured 5 × 10 meters (50 m²), and at harvest, three samples were collected per plot using a 1 m² quadrat. Fresh weights of the harvested samples were recorded, after which 500 g subsamples were oven-dried to determine dry matter yield per hectare. The authors reported that only one harvest was conducted per year at each location.

Detailed climatic data for the study period were subsequently acquired from the General Directorate of Meteorology and are summarised in Table 1.

Table 1. Climate data for the years during which the fertilisation study was conducted

Year of Experiment	Period	Average Highest Temperature (°C)	Average Lowest Temperature (°C)	Average Temperature (°C)	Average Relative Humidity (%)	Total Precipitation (mm)
Palandöken						
1990	April-October	20.5	3.7	12.4	61.9	196.4
1991	April-October	21.1	4.8	13.3	62.9	219.3
1992	April-October	19.1	3.4	11.6	64.0	285.8
1990	Annual	11.6	-3.7	3.9	70.1	343.7
1991	Annual	12.1	-2.3	5.0	70.5	373.5
1992	Annual	9.5	-5.0	2.4	70.6	411.6
Erciş						
1990	April-October	22.8	7.0	14.3	64.5	161.6
1991	April-October	23.5	8.1	15.2	64.1	206.5
1992	April-October	21.2	6.5	13.2	62.2	213.4
1990	Annual	15.0	0.7	7.0	67.4	334.7
1991	Annual	15.4	1.7	7.8	67.2	483.4
1992	Annual	12.6	-0.6	5.3	65.0	406.3
Oltu						
1990	April-October	23.2	9.4	16.4	59.5	227.3
1991	April-October	24.2	10.4	17.5	57.6	230.5
1992	April-October	21.9	8.5	15.4	60.4	277.8
1990	Annual	15.5	3.4	9.3	63.2	400.1
1991	Annual	16.0	4.1	10.0	62.6	411.9
1992	Annual	13.0	1.2	7.0	63.8	428.5

Source: Anonymous (1993)

As illustrated in Table 1, the initial year of the study (1990) was characterised by lower precipitation levels across all study sites relative to subsequent years. Both the annual cumulative precipitation and the total rainfall observed during the vegetative growth period (April to October) were markedly lower compared to other years. Conversely, in the third year of the study, precipitation levels during the vegetation period were comparatively higher across all districts.

Fertilisation Experiment Data

The summarised data from the fertilisation study conducted by Mermer et al. (1996) on natural rangelands are presented in Table 2, categorised by poor, moderate, and good rangeland conditions.

Table 2. Results of the fertilisation experiment conducted on poor, moderate, and good condition rangelands

P Doses	N Doses	Poor Condition Rangelands			Moderate Condition Rangelands			Good Condition Rangelands		
		1990	1991	1992	1990	1991	1992	1990	1991	1992
0	0	447	535	310	994	1463	835	1705	3545	2077
0	30	501	900	440	1076	1260	948	2284	2845	2435
0	60	604	1285	1125	1045	1450	1360	2192	3173	3130
0	90	533	1453	1310	1390	1505	1270	2449	4265	3045
40	0	385	490	325	1211	1950	1727	1920	3038	2393
40	30	503	965	630	1718	2935	2185	2524	4113	3130
40	60	561	1890	1273	1713	3230	2513	2295	4420	3120
40	90	722	2143	1948	1968	3753	2425	2766	4510	3758
80	0	434	505	260	1063	2438	1385	2260	3590	2363
80	30	625	1050	523	1733	2245	2153	2284	3745	3050
80	60	667	1973	1655	1965	3573	2685	2196	4318	3132
80	90	613	2465	2220	1755	3330	2035	3350	5525	3435

Source: Mermer et al. (1996). LSD values from the original study are not included, as the data were used exclusively for economic and regression-based analyses in the present study.

When the pasture hay yields in Table 2 are examined, the first year, which was drought compared to the subsequent years, yielded the lowest hay yields across all locations. Hay yields in the third year, which received relatively more rainfall, also lagged behind hay yields in the second year.

Handling the Data

Given that the primary objective of rangeland fertilisation is to enhance dry matter yield, the net increases in hay production resulting from fertiliser application were analysed using regression techniques. For this purpose, the Net Hay Yield variable, representing the increase in hay yield due to fertilisation, was calculated by subtracting the dry hay yields obtained from unfertilized control plots from those of fertilised plots. This procedure was conducted separately for each rangeland condition class and study year. The Gross Benefit variable, which represents the positive gross revenue difference between the fertiliser applied and non-applied plots, was also generated following the same procedure and will be explained later.

The regression model incorporated climatic variables such as total precipitation, relative humidity, and mean temperature, in addition to nitrogen and phosphorus fertiliser doses and rangeland condition classifications. Since the application of nitrogen and phosphorus is expected to improve vegetative cover over time, the cumulative effects of fertiliser applied in earlier years were considered for the second and third years of the study. To account for this temporal accumulation, three derived variables, Nitrogen Effect, Phosphorus Effect, and Total Effect were generated. That is, in the first year, plots receiving 0, 30, 60, and 90 kg ha^{-1} of nitrogen were assigned values of 0, 1, 2, and 3, respectively. These values were multiplied by two for the second year and by three for the third year to construct the Nitrogen Effect variable. The Phosphorus Effect variable was generated using an analogous procedure based on phosphorus application rates. The Total Effect variable was then calculated as the sum of these two fertilisation effect variables.

Data Analysis

In the real world, multiple factors often influence a dependent variable, making it essential to isolate the effects of each independent variable. The *ceteris paribus* assumption, holding other factors constant, enables this and helps identify causation. Linear regression, particularly the Ordinary Least Squares (OLS) method, is widely used in econometrics to estimate these relationships (Gujarati, 2011). Regression coefficients in this approach help interpret the impact of each independent variable on the outcome.

The study by Mermer et al. (1996) was conducted across geographically dispersed rangeland sites classified into distinct condition categories, introducing considerable heterogeneity into the data structure. To address this heterogeneity and ensure unbiased estimation, panel data regression methods are recommended (Baltagi, 2005). The most widely utilised panel data approaches are the fixed effects (FE) and random effects (RE) models. The FE model examines variations in predictor-outcome relationships within entities (here, the permanent rangeland sites). In contrast, the RE model assumes that differences across entities are random and uncorrelated with the explanatory variables. Given the structure of the dataset, the RE model initially appeared to be the most suitable analytical choice. Nevertheless, results from the Breusch–Pagan Lagrange Multiplier test failed to reject the null hypothesis of no panel effect, thereby supporting the use of a pooled regression model for the final analysis. In addition to regression modelling, descriptive statistical techniques were employed to summarise and characterise the variables under investigation (Torres-Reyna, 2007; Cameron & Trivedi, 2010; Adkins & Hill, 2011).

A pooled linear regression model can be written in the equation below (Gujarati, 2011);

$$Y_i = \alpha_1 + \propto_2 D_{2i} + \cdots + \propto_k D_{ki} + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots\ldots + \beta_n X_{ni} + u_i \qquad \text{(Eq.1)}$$

In this equation, Y_i denotes the dependent variable, while α represents the intercept term. The variables X_i and D_i correspond to continuous and dummy explanatory variables, respectively. The coefficients β_1 through β_n indicate the slopes associated with each independent variable, where k and n represent the k^{th} dummy variable and n^{th} continuous variable. The subscript i refers to the i^{th} observational unit, and u_i denotes the stochastic error term.

In the regression models, the categorical variables were represented by dummy variables, whose number was one less than the classification of the qualitative variable (Gujarati, 2011). In this study, the rangeland condition variable had three categories. So, it was represented by two dummies. Since the dummy variable for poor condition rangeland was not included in the regression model, the coefficients of other dummy variables should be interpreted according to the reference category (poor condition). The coefficients of other continuous independent variables represent the marginal change in the dependent variable as a result of a one-unit change in the continuous dependent variable of interest, at *ceteris paribus.*

Consistent with the above explanations, Nethayyield and Grossbenefit variables were regressed as a function of the variables, as explained in Table 3.

Table 3. Variables Included in the Regression Model

Variable	Description
Nethayyield	Difference in hay yield between fertilised plots and control plots (kg ha^{-1})
Grossbenefit	Difference in gross revenue between fertilised plots and control plots (TRY ha^{-1})
Nitrogen	Pure nitrogen applied to plots (kg ha^{-1})
Phosphorus	Pure phosphorus applied to plots (kg ha^{-1})
Condition	Rangeland condition class (1: Poor; 2: Moderate; 3: Good)
Nitrosq	Squared term for nitrogen application rates
Phospsq	Squared term for phosphorus application rates
PhosNitro	The interaction term between nitrogen and phosphorus application
Neffect	The cumulative effect of nitrogen across years
Peffect	The cumulative effect of phosphorus across years
Teffect	Synergistic cumulative effect of nitrogen and phosphorus
Seasonalpr	Total precipitation (mm) during the vegetation period (April–October)
Seasonhum	Average relative humidity (%) during the vegetation period (April–October)
Seasontemp	Average temperature (°C) during the vegetation period (April–October)

Normality assumption, heteroskedasticity, multicollinearity and model specification error were tested using the Skewness and Kurtosis test, the Breusch-Pagan test, the variance inflation factor (VIF) and the Stata command link test (Cameron & Trivedi, 2010). Data analysis was performed using the Stata SE 14.2 software package (StataCorp, 2015).

Economic Analysis

The economic analysis utilised the partial budget method, which evaluates only the changes

in income and expenses attributable to a specific intervention, while excluding unaffected elements (Olson, 2010). Given the study's focus on how fertilisation affects hay yield in rangelands, the analysis centred on changes in income from rangeland hay and fertiliser expenses for different fertiliser combinations and doses. Since rangeland hay lacks a market price, Rangeland forage value was estimated using the surrogate market valuation method. (NRC, 1999; Cousins, 1999; Rehber, 1999; Torrell et al., 2014; Kara et al., 2019). Accordingly, meadow hay was used as a substitute for rangeland forage, and the 2024 meadow hay prices available from the Erzurum Commodity Exchange were used as a financial proxy to value the rangeland forage (Kara et al. 2019). In calculating fertiliser expenses, the 2024 prices for triple super phosphate (TSP) for phosphorus and ammonium sulphate fertiliser (AS) for nitrogen were used (Anonymous, 2024). As the revenue and expense calculations for all three years were based on 2024 prices, no adjustments to fixed prices were necessary.

Gross revenue was calculated by subtracting total fertiliser cost from total forage revenue. Forage revenue represents the total financial equivalent of rangeland forage, calculated by multiplying the total amount of rangeland forage by its proxy meadow hay price (Karagölge 2001). The Gross Benefit was then calculated by deducting the gross revenue of the control plots from that of the fertiliser-treated plots.

3. Results and Discussion

Visual Review of Fertilisation Data

Upon examining the rangeland hay yields presented in Table 2, it is evident that the lowest hay yield across all locations occurred during the first year of the study, which was characterised by drought conditions. Interestingly, hay yields recorded in the third year, despite comparatively higher precipitation, remained below those obtained in the second year.

These yield variations suggest that forage production in rangelands is shaped not only by climatic conditions, but also by input–output dynamics. One of the foundational principles in production economics is the law of diminishing returns, which posits that, under constant production technology, increasing the quantity of a single input (e.g., nitrogen, as in this context) while holding others fixed (*ceteris paribus*) will eventually yield progressively smaller marginal gains in output (Heady & Dillon, 1961). In this study, the presence of this response pattern was preliminarily examined across three rangeland types by visually assessing hay yields in fertiliser-treated rangeland plots prior to proceeding with further analyses.

Table 4. Fertilisation study: three-year averages of hay yields and net yields (1990-1992)

P Doses	N Doses	Average Hay Yield			Net Hay Yield		
		Poor Condition	Moderate Condition	Good Condition	Poor Condition	Moderate Condition	Good Condition
0	0	431	1097	2442	0	0	0
0	30	614	1095	2521	183	-3	79
0	60	1005	1285	2832	574	188	389
0	90	1099	1388	3253	668	291	811
40	0	400	1629	2450	-31	532	8
40	30	699	2279	3256	269	1182	813
40	60	1241	2485	3278	811	1388	836
40	90	1604	2715	3678	1174	1618	1236
80	0	400	1629	2738	-31	531	295
80	30	733	2044	3026	302	946	584
80	60	1432	2741	3215	1001	1644	773
80	90	1766	2373	4103	1335	1276	1661

Source: Derived from Table 2.

Poor Condition Rangeland: As shown in Table 2, the law of diminishing returns was evident in the 1990 data for plots treated with nitrogen alone, without phosphorus application. However, in 1991 and 1992, the quadratic relationship assumed by this law between nitrogen doses and hay yield did not emerge in the same plots. This discrepancy can be attributed to higher rainfall levels recorded at the poor rangeland site during those years compared to the trial's initial year. In other words, elevated soil moisture availability in the second and third years likely enhanced nitrogen

efficacy (Devkota et al. 2025), masking the quadratic yield response typically assumed by the law of diminishing returns (Dhakal & Lange 2021). The highest nitrogen dose employed in the trial was 90 kg ha^{-1}; yet, to observe this curvature effect, i.e., to identify the inflexion point, higher nitrogen levels would have needed to be tested.

Similarly, across all years, including the arid initial year, plots treated with 40 kg ha^{-1} of phosphorus did not exhibit a clear inflexion point in response to increasing nitrogen doses. The absence of such a pattern even in the arid first year can be explained by phosphorus enhancing nitrogen's efficiency (Wang et al. 2022). By contrast, plots receiving 80 kg ha^{-1} of phosphorus exhibited a quadratic relationship between nitrogen application and dry forage yield, aligned with the law of diminishing returns, but only during the arid initial year; the effect dissipated in the wetter subsequent years most likely due to the high soil moisture in last two years that increased phosphorus mobility (Mariotte et al., 2020).

Moderate Condition Rangeland: Throughout the initial two years of the study, plots with no phosphorus applications exhibited a consistent increase in dry forage yield as nitrogen doses rose, and no identifiable inflexion point emerged to mark the threshold anticipated by the law of diminishing returns. By the third year, however, the highest yield was achieved at a nitrogen level of 60 kg ha^{-1}, followed by a decline at 90 kg ha^{-1}. This shift suggests that the diminishing returns effect in phosphorus-deficient plots became perceptible only in the latter phase of the study, marking a delayed ecological response within the moderate rangeland condition.

In plots with 40 kg phosphorus applications, no nitrogen threshold indicative of diminishing returns was observed during the study's initial two years; forage yield increased consistently with rising nitrogen doses. However, in 80 kg phosphorus-treated plots, the law of diminishing returns, typically modelled through quadratic production functions in agronomic systems, was evident in both the first and third years. Although the second year largely mirrored this trend, the quadratic relationship was disrupted by an anomalously low yield (2,245 kg) at 30 kg nitrogen, which fell below the yield recorded in non-fertilised plots. In contrast, plots receiving 60 kg of nitrogen exhibited a significant yield increase, suggesting potential data inconsistency. If the yield for the 30 kg of nitrogen dose were misreported and should be 3,245 kg, as indicated by comparative patterns, then the principle of diminishing returns would apply uniformly across all years, reinforcing the sensitivity of yield outcomes to input ratios, environmental conditions, and data accuracy.

Good Condition Rangeland: In the first year of the study, good condition rangeland plots with no phosphorus applications exhibited hay yield responses to increasing nitrogen doses consistent with the law of diminishing returns. However, this effect did not manifest in the second and third years, during which hay yield continued to rise with higher nitrogen levels.

Across all three years, plots treated with 40 kg ha^{-1} of phosphorus demonstrated a steady increase in dry forage yield with rising nitrogen doses, and the inflexion point anticipated by the law of diminishing returns could not be identified, even during the drought-prone year of 1990. As explained earlier, this may be attributable to the fact that, under water-limited conditions, phosphorus application can enhance nitrogen uptake efficiency (Wang et al., 2022), thereby delaying or suppressing the onset of diminishing marginal returns at otherwise critical nitrogen thresholds. The synergistic effect is particularly evident in drought-stressed plots, where phosphorus-mediated improvements in root development and nutrient transport offset nitrogen saturation effects (Schleuss et al., 2020; He & Dijkstra, 2014). By contrast, in plots receiving 80 kg ha^{-1} of phosphorus, the diminishing returns effect was evident in the first year of the study but not in the subsequent, relatively wetter years.

Regression Analysis Results

Prior to interpreting the regression coefficients, diagnostic tests were conducted to evaluate model specification and overall validity. The F-statistics associated probability values, and both the R-squared and adjusted R-squared metrics confirmed a satisfactory goodness-of-fit for both models (see Tables 5 and 6). The assumption of normality was upheld, as indicated by the Skewness and Kurtosis test ($p > 0.05$). Moreover, the Link test, which assesses whether the model is correctly specified, failed to reject the null hypothesis, suggesting no specification error.

However, the Breusch–Pagan test identified the presence of heteroskedasticity ($p < 0.05$) exclusively in the *NetHayYield* model. In addition,

variance inflation factors (VIFs), particularly involving squared and interaction terms, indicated substantial multicollinearity. Nonetheless, such multicollinearity, when arising from interaction terms and their constituent variables, is considered "inessential ill-conditioning" (Francoeur, 2013) and does not compromise model validity (Allison, 2012). To correct for heteroskedasticity in the *NetHayYield* model, robust standard errors were applied. Taken as a whole, these diagnostic outcomes affirm that both models maintain robust explanatory capacity and are appropriately specified for subsequent interpretation.

When interpreting the regression coefficients, it is important to recognise that *NetHayYield* and *GrossBenefit* capture the positive differential between fertilised and non-fertilised plots, reflecting changes in hay yield and gross revenue, respectively. Accordingly, the effect of rangeland condition class should be understood as its moderating influence on the response to fertilisation, rather than as an independent driver of yield. The models indicate that rangeland condition, in isolation, does not exert a statistically significant effect on *NetHayYield* or *GrossBenefit* across the three condition classes. While the moderate-condition rangeland site exhibited notable improvements in both outcomes, these gains did not reach statistical significance relative to the poor-condition site. Conversely, the good-condition rangeland showed a markedly diminished response to fertilisation, suggesting that its inherent productivity may limit the marginal benefit of nutrient supplementation.

These findings imply that fertiliser interventions may yield greater returns when targeted toward moderately degraded rangelands, where the potential for responsive improvement remains high, rather than on sites already in good condition, where additional inputs may offer limited benefit.

Table 5. Results of the least-squares pooled regression analysis for rangeland hay

NetHayYield	**Coefficient**	**Robust Std. Error**	**t**	**P**	**VIF**
Rangeland Condition					
Moderate	152.660	150.989	1.010	0.315	4.22
Good	57.038	309.287	0.180	0.854	14.92
Phosphorus fertilizer	12.281	4.619	2.660	0.009	16.72
Phosphorus squared	-0.155	0.048	-3.260	0.002	13.02
Nitrogen fertilizer	4.078	4.153	0.980	0.329	16.66
Nitrogen squared	-0.018	0.041	-0.440	0.662	12.25
Phosphorus x Nitrogen interaction	0.081	0.034	2.360	0.021	4.30
Temporal effect of fertilisation	78.848	28.928	2.730	0.008	7.54
Seasonal total precipitation	1.594	2.359	0.680	0.501	6.24
Seasonal average humidity	76.978	41.075	1.870	0.064	6.70
Seasonal average temperature	81.517	66.880	1.220	0.226	7.53
Constant	-6461.024	2782.667	-2.320	0.022	
Number of observations	: 108	F (11: 96)	: 18.24	Mean VIF	: 10.01
R^2	: 67.64	Adjusted R^2	: 63.93	p	: 0.000

VIF: Variance Inflation Factor

On the other hand, phosphorus application exhibits a significantly positive effect on both *NetHayYield* and *GrossBenefit*. However, its squared term has a significant negative coefficient, indicating that although yield and revenue increase with incremental phosphorus application, the rate of increase declines as phosphorus levels rise, suggesting diminishing marginal returns.

A similar pattern emerges with nitrogen in the *NetHayYield* model, where the leading coefficient is positive and the quadratic term is negative, suggesting an initially increasing yield response that eventually plateaus or declines, consistent with the law of diminishing returns. However, in the *GrossBenefit* model, both the main and quadratic coefficients for nitrogen are negative, though statistically insignificant. This indicates that, from an economic standpoint, increasing nitrogen dosage does not enhance gross benefit and may even contribute to declining returns when considered independently of phosphorus interaction.

The phosphorus × nitrogen interaction term is statistically significant in both models, indicating a synergistic relationship (Wang et al., 2022; Schleuss et al., 2020; He & Dijkstra, 2014). This suggests that although nitrogen alone does not yield a significant effect, its combined application with phosphorus enhances both yield and revenue outcomes.

To assess the cumulative effect of fertilisation over time, a temporal variable was included as previously described. The regression results show a positive and significant impact of this variable on both *NetHayYield* and *GrossBenefit*, supporting the inclusion of time-structured variables to capture delayed and cumulative effects.

Table 6. Results of the least-squares pooled regression analysis for *GrossBenefit*

GrossBenefit	**Coefficient**	**Std. Error**	**t**	**P**	**VIF**
Rangeland Condition					
Moderate	641.174	678.625	0.940	0.347	4.22
Good	239.558	1276.663	0.190	0.852	14.92
Phosphorus fertilizer	29.674	19.502	1.520	0.131	16.72
Phosphorus squared	-0.652	0.207	-3.150	0.002	13.02
Nitrogen fertilizer	-25.729	18.958	-1.360	0.178	16.66
Nitrogen squared	-0.076	0.173	-0.440	0.662	12.25
Phosphorus x Nitrogen interaction	0.339	0.142	2.390	0.019	4.30
Temporal effect of fertilisation	331.160	118.834	2.790	0.006	7.54
Seasonal total precipitation	6.696	10.721	0.620	0.534	6.24
Seasonal average humidity	323.309	183.440	1.760	0.081	6.70
Seasonal average temperature	342.370	234.024	1.460	0.147	7.53
Constant	-27136.300	11247.540	-2.410	0.018	
Number of observations	: 108	F (11: 96)	: 5.83	Mean VIF	: 10.01
R^2	: 40.05	Adjusted R^2	: 3.19	p	: 0.000

VIF: Variance Inflation Factor

Additionally, seasonal precipitation and temperature did not significantly affect either response variable. However, the effect of temperature, while statistically insignificant, may hold interpretive value. In contrast, seasonal humidity exhibited a marginally significant effect across both models, suggesting that while precipitation and temperature may play limited roles, humidity may have a modest effect on hay yield and gross revenue. This can be explained by the fact that relative humidity can influence crop yield more directly than precipitation by regulating transpiration and water stress (Notes for Ag, 2022). Thus, high humidity can reduce transpiration, thereby conserving plant water under limited soil moisture conditions, while low humidity increases transpiration, leading to water stress, especially when soil moisture is insufficient.

Economic Analysis Results

Based on partial budgeting, the economic analysis results are presented across the three rangeland types as follows.

Poor Condition Rangeland: Table 7 presents the economic analysis results from the fertilisation study conducted by Mermer et al. (1996) on a poor condition natural rangeland site.

Table 7. Partial Budgeting Results for Poor Rangeland Sites

P Rates	N Rates	Phosphorus Fertiliser Cost	Nitrogen Fertiliser Cost	Total Fertiliser Cost	Average Forage Revenue	Average Gross Revenue	Gross Benefit
0	0	0.0	0.0	0.0	1765.7	1765.7	0.0
0	30	0.0	1285.7	1285.7	2516.0	1230.3	-535.4
0	60	0.0	2571.4	2571.4	4119.1	1547.7	-218.0
0	90	0.0	3857.1	3857.1	4504.5	647.4	-1118.3
40	0	876.2	0.0	876.2	1640.0	763.8	-1001.9
40	30	876.2	1285.7	2161.9	2867.3	705.4	-1060.4
40	60	876.2	2571.4	3447.6	5089.5	1641.8	-123.9
40	***90***	***876.2***	***3857.1***	***4733.3***	***6577.8***	***1844.4***	***78.7***
80	0	1752.4	0.0	1752.4	1638.6	-113.7	-1879.5
80	30	1752.4	1285.7	3038.1	3003.9	-34.2	-1799.9
80	60	1752.4	2571.4	4323.8	5869.8	1546.0	-219.7
80	90	1752.4	3857.1	5609.5	7240.6	1631.1	-134.7

Source: The calculation of fertiliser costs was derived from the data presented in Table 2. The fertilisers utilised in this analysis were triple super phosphate (TSP) and ammonium sulphate (AS), which possess effective phosphorus and nitrogen rates of 42% and 21%, respectively (GÜBRETAŞ, 2025). As reported by Anonymous (2024), the unit prices for TSP and AS were 9.2 TL/kg and 9 TL/kg, respectively.

The findings reported by Mermer et al. (1996), as outlined in Table 4, illustrate that fertilisation significantly increased dry forage yield on degraded rangeland, from 431 kg ha^{-1} in unfertilized plots to 1766 kg ha^{-1} under fertilisation. Nonetheless, forage productivity remained suboptimal across all treatments. Despite statistically significant differences in phosphorus application levels, the yield improvements were deemed economically unjustifiable, primarily due to the minimal legume presence within the botanical composition.

While the highest recorded yield corresponded to the application of 90 kg ha^{-1} nitrogen and 80 kg ha^{-1} phosphorus (Tables 2 and 4), the researchers advocated for a more moderate fertilisation strategy, 60 kg ha^{-1} nitrogen and 40 kg ha^{-1} phosphorus, to promote economically and ecologically sustainable rangeland management.

Complementing these agronomic insights, partial budgeting outcomes from the present study (Tables 2 and 4) reveal a nuanced distinction between biological output and economic feasibility. Although the 90N–80P treatment achieved maximum yield, it failed to deliver economic viability. Instead, the treatment combining 90 kg ha^{-1} nitrogen with 40 kg ha^{-1} phosphorus generated the highest gross revenue and gross benefit, highlighting the importance of cost-efficiency and strategic input allocation in rangeland fertilisation.

Moderate Condition Rangeland: Mermer et al. (1996) reported, based on the fertilisation outcomes presented in Table 2 and 4, that the three-year fertilisation results on moderate condition rangeland exhibited distinct characteristics compared to poor condition rangeland. On average, hay yield increased by a factor of 1.5 over the three years, with the most substantial improvements attributed to phosphorus applications. The researchers explained this enhancement by citing two primary factors: a higher proportion of legumes in the botanical composition and the inherently low phosphorus levels in the soil (Mermer et al., 1996).

Although the highest yield was recorded in plots receiving 60–90 kg ha^{-1} nitrogen and 40–80 kg ha^{-1} phosphorus, the researchers emphasized that, from both an economic and ecological sustainability standpoint, an application rate of 40 kg ha^{-1} nitrogen (Most likely, they misspelled it as 40 kg ha^{-1} instead of 30 kg ha^{-1}, since 40 kg of nitrogen is not included in the studied nitrogen rates.) and 40 kg ha^{-1} phosphorus would be more appropriate for moderate condition rangeland, particularly for promoting a balanced botanical composition.

In line with this agronomic assessment, partial budgeting analysis (Table 8) confirmed to the researchers that the fertiliser doses yielding the maximum forage production were not economically viable. Instead, the plots receiving 40 kg ha^{-1} phosphorus and 30 kg ha^{-1} nitrogen achieved the highest gross revenue and gross benefit, thereby justifying a recommendation of 40 kg ha^{-1} phosphorus and 30 kg ha^{-1} nitrogen as the economically optimal fertilisation strategy for moderate condition rangelands.

Table 8. Partial Budgeting Results for Moderate Condition Rangeland Sites

P Rates	N Rates	Phosphorus Fertiliser Cost	Nitrogen Fertiliser Cost	Total Fertiliser Cost	Average Forage Revenue	Average Gross Revenue	Gross Benefit
0	0	0.0	0.0	0.0	4499.1	4499.1	0.0
0	30	0.0	1285.7	1285.7	4488.1	3202.4	-1296.6
0	60	0.0	2571.4	2571.4	5268.5	2697.1	-1802.0
0	90	0.0	3857.1	3857.1	5692.2	1835.0	-2664.0
40	0	876.2	0.0	876.2	6680.3	5804.1	1305.0
40	***30***	***876.2***	***1285.7***	***2161.9***	***9345.3***	***7183.4***	***2684.3***
40	60	876.2	2571.4	3447.6	10189.9	6742.2	2243.2
40	90	876.2	3857.1	4733.3	11132.9	6399.5	1900.5
80	0	1752.4	0.0	1752.4	6677.5	4925.2	426.1
80	30	1752.4	1285.7	3038.1	8379.0	5340.9	841.9
80	60	1752.4	2571.4	4323.8	11238.1	6914.3	2415.2
80	90	1752.4	3857.1	5609.5	9730.7	4121.1	-377.9

Source: Calculated based on the data presented in Table 4. The calculations about cost and revenue are consistent with those presented in Table 7.

Good-Condition Rangeland: Mermer et al. (1996) reported that, even in unfertilized plots within good-condition rangelands, dry forage yield reached levels comparable to those observed in fertilised plots on moderate-condition rangelands. They also noted that the relative contribution of fertilisation to yield enhancement was notably lower than in degraded or moderate-condition sites, with improvements not exceeding 70%. The authors further noted that the differences among nitrogen treatments were statistically significant at the 1% level, while differences among phosphorus treatments were significant at the 5% level, as the nitrogen–phosphorus interaction effect was statistically insignificant. Because the highest dry forage yield was obtained from plots treated with 90 kg ha^{-1} nitrogen and 80 kg ha^{-1} phosphorus, Mermer et al. (1996) suggested that if resources are sufficient, this fertilisation rate could be recommended for good-condition rangelands. Under limited resource allocations, however, they proposed the combination of 40 kg ha^{-1} nitrogen and 40 kg ha^{-1} phosphorus, which yielded the most outstanding forage output per unit of fertiliser applied.

Although the highest hay yield was obtained from plots receiving 80 kg ha^{-1} phosphorus and 90 kg ha^{-1} nitrogen, it did not generate a gross revenue and so gross benefit significantly differing from the gross revenue and gross benefit obtained from the plots treated with 40 kg ha^{-1} phosphorus and 30 kg ha^{-1} nitrogen (Table 9). Consequently, even in sufficient resource availability, the recommendation of 80 kg ha^{-1} phosphorus and 90 kg ha^{-1} nitrogen appears economically unjustified. Therefore, as in the case of moderate condition rangelands, a fertilisation rate of 40 kg ha^{-1} phosphorus and 30 kg ha^{-1} nitrogen may likewise be considered appropriate for good-condition rangelands.

Table 9. Partial Budgeting Results for Good Condition Rangeland Sites

P Rates	N Rates	Phosphorus Fertiliser Cost	Nitrogen Fertiliser Cost	Total Fertiliser Cost	Average Forage Revenue	Average Gross Revenue	Gross Benefit
0	0	0.0	0.0	0.0	10013.6	10013.6	0.0
0	30	0.0	1285.7	1285.7	10337.5	9051.8	-961.8
0	60	0.0	2571.4	2571.4	11609.8	9038.4	-975.2
0	90	0.0	3857.1	3857.1	13337.3	9480.2	-533.4
40	0	876.2	0.0	876.2	10046.4	9170.2	-843.4
40	***30***	***876.2***	***1285.7***	***2161.9***	***13348.2***	***11186.3***	***1172.8***
40	60	876.2	2571.4	3447.6	13441.2	9993.5	-20.0
40	90	876.2	3857.1	4733.3	15079.8	10346.5	332.9
80	0	1752.4	0.0	1752.4	11224.4	9472.1	-541.5
80	30	1752.4	1285.7	3038.1	12408.0	9369.9	-643.7
80	60	1752.4	2571.4	4323.8	13182.9	8859.1	-1154.5
80	*90*	*1752.4*	*3857.1*	*5609.5*	*16823.7*	*11214.1*	*1200.6*

Source: Calculated based on the data presented in Table 4. The calculations about cost and revenue are consistent with those presented in Table 7.

4. Conclusion

This study aimed to determine the economically optimal nitrogen and phosphorus application rates by adopting a more comprehensive approach than previous research. It integrated different pasture condition classes, economic analysis, and climate parameters such as precipitation, relative humidity and average temperature over a broader timescale, with the goal of supporting sustainable and economically viable fertilisation strategies to enhance pasture productivity. The analysis was based on data from fertilisation trials conducted by Mermer et al. (1996) in pastures classified as poor, moderate, and good condition.

The study demonstrated that forage yield responses to fertilisation in rangeland systems are shaped by a complex interplay of ecological conditions, input synergies, and temporal dynamics. Visual assessments of hay yield across the three rangeland types revealed patterns broadly consistent with the law of diminishing returns, with phosphorus application notably enhancing nitrogen efficiency, particularly under drought stress. These inflection patterns varied not only by input level but also by rangeland condition and year, highlighting the ecological sensitivity of nutrient interactions

Regression analyses validated many of these visual interpretations. Phosphorus application

exerted a significantly positive effect on both *NetHayYield* and *GrossBenefit*, although the presence of negative quadratic coefficients indicated declining marginal returns at higher doses. Nitrogen effects mirrored these patterns in the *NetHayYield* model but failed to show statistical significance in the *GrossBenefit* framework, suggesting that nitrogen's economic efficiency depends heavily on interaction with phosphorus. The statistically significant phosphorus × nitrogen interaction term across both models confirms the synergistic relationship implied by the visual data.

Temporal factors also proved influential. The significance of time-structured variables highlights the cumulative and delayed nature of fertilisation responses, particularly in moderate-condition rangelands where yield improvements emerged later in the study. Seasonal humidity, while only marginally significant, appeared more relevant than precipitation or temperature, suggesting its potential as a moderating climatic variable.

Taken together, these findings reinforce the importance of integrated agronomic and econometric approaches in evaluating rangeland fertilisation. The results support a nuanced management strategy that balances input efficiency, ecological sustainability, and economic viability, especially in the context of variable climatic pressures and site-specific responses.

Based on regression diagnostics, economic efficiency analysis, and yield responsiveness across rangeland types, optimal fertilisation strategies were developed to balance ecological sustainability with agronomic productivity.

- The quadratic response in phosphorus indicates yield saturation beyond 40–80 kg ha^{-1}, warranting a conservative upper limit.
- Nitrogen shows weak standalone effects but exhibits synergistic value when paired with phosphorus in moderate to good condition rangelands.
- Economic analysis confirms diminishing marginal returns at higher input levels, especially in good-condition sites.

Table 10. Recommended fertiliser rates across rangeland conditions

Rangeland Condition	Phosphorus Rate	Nitrogen Rate	Rationale
Poor	40 kg ha^{-1}	90 kg ha^{-1}	Maximises gross benefit with significant yield response
Moderate	40 kg ha^{-1}	30 kg ha^{-1}	Balances input costs with output efficiency; avoids marginal gains
Good	40 kg ha^{-1}	30 kg ha^{-1}	Higher inputs yield marginal gains; lower rates are more economically sustainable.

Based on the findings, the following conclusions are drawn:

- Fertiliser recommendations should be site-specific, reflecting a balance between ecological conditions and economic feasibility to optimise resource use and agronomic outcomes.
- Poor-condition rangelands merit prioritisation, not necessarily for short-term economic gains, but for their potential in productivity recovery and ecological restoration. The objective is to restore their yield capacity toward historical benchmarks, contributing to resilient agricultural landscapes.
- Achieving sustainable benefits and upholding environmental stewardship require continuous monitoring and adaptive fertilisation strategies. Such approaches empower stakeholders to respond dynamically to evolving conditions and mitigate long-term risks.

References

Adkins, L. C., & Hill, R. C. (2011). Using Stata for principles of econometrics. John Wiley & Sons.

Algan, D., Aydın, İ., & Ocak, N. (2018). Economic analysis of fertilization based on nutritional value of rangeland: A new opinion. Anadolu Tarım Bilimleri Dergisi, 33(3), 246–253. https://doi.org/10.7161/omuanajas.404991

Allison, P. D. (2012). When can you safely ignore multicollinearity? Statistical Horizons. https://statisticalhorizons.com/multicollinearity/

Altın, M., Gökkuş, A., & Koç, A. (2005). Meadow and pasture rehabilitation. Ministry of Agriculture and Rural Affairs.

Altın, M., Tuna, C., & Gür, M. (2010). Effects of fertiliser application on forage production and botanical composition of floodplain and steppe rangelands of Tekirdağ. Tekirdağ Ziraat Fakültesi Dergisi, 7(2), 191–198.

Anonymous. (1993). Meteorological data. Turkish State Meteorological Service.

Anonymous. (2018). Rangeland regulation under Law No. 4342. https://www.mevzuat.gov.tr

Anonymous. (2024). Tarım Kredi fertiliser prices. https://www.devletdestekli.com/tarim-kredi-dap-26-azot-gubre-fiyatlari-guncel/

Anonymous. (2025a). Meadow, pasture and forage crops. Turkish Ministry of Agriculture and Forestry. https://www.tarimorman.gov.tr/Konular/Bitkisel-Uretim/Cayir-Mera-ve-Yem-Bitkileri/

Anonymous. (2025b). Official records. Eastern Anatolia Agricultural Research Institute.

Avağ, A., Koç, A., & Kendir, H. (2012). Result report for the National Rangeland Utilisation and Management Project (TÜBİTAK Project No. 106G017). Ministry of Agriculture and Forestry.

Aydın, F., & Uzun, F. (2005). Yield response of rangeland forage to nitrogen and phosphorus under variable moisture conditions. Turkish Journal of Agriculture and Forestry, 29(4), 267–274.

Aydın, İ., & Uzun, F. (2005). Nitrogen and phosphorus fertilisation of rangelands affects yield, forage quality and botanical composition. European Journal of Agronomy, 23(1), 8–14. https://doi.org/10.1016/j.eja.2004.08.001

Balabanlı, C., Albayrak, S., Türk, M., & Yüksel, O. (2009). Problems on rangeland law No. 4342: Application and solutions. Turkish Journal of Forestry, 7(1), 75–81. https://doi.org/10.18182/tjf.94922

Baltagi, B. H. (2005). Econometric analysis of panel data (3rd ed.). John Wiley & Sons.

Cameron, A. C., & Trivedi, P. K. (2010). Microeconometrics using Stata (Rev. ed.). Stata Press.

Cousins, B. (1999). Invisible capital: The contribution of communal rangelands to rural livelihoods in South Africa. Development Southern Africa, 16(2), 299–318.

Cowie, A., Waters, C., Garland, F., Orgill, S., Baumber, A., Cross, R., O'Connell, D., & Metternicht, G. (2019). Assessing resilience to underpin implementation of land degradation neutrality. Environmental Science & Policy, 100, 37–46. https://doi.org/10.1016/j.envsci.2019.06.002

Delalandre, F., Minden, V., Vallicrosa, H., Tateno, R., & Vesk, P. A. (2025). Plasticity in plant traits to fertilisation treatments varies across ecological indicators and species. Annals of Botany, 135(4), 789–803. https://doi.org/10.1093/aob/mcad022

Demirel, A., & Türk, M. (2017). The effects of fertilization on yield and quality in the Burdur-Hacılar village sole pasture. Ziraat Fakültesi Dergisi, 12(1), 68–74.

Devkota, L., Shrestha, R. K., Khatri, K. B., Acharya, B., & Sharma, S. (2025). Interactive effect of soil moisture content and nitrogen fertilizer sources on growth and nitrogen uptake in maize. Agricultura, 14728.

Dhakal, C., & Lange, K. (2021). Crop yield response functions in nutrient application. Agronomy Journal, 113(6), 5222–5234. https://doi.org/10.1002/agj2.20863

di Virgilio, A., Lambertucci, S. A., & Morales, J. M. (2019). Sustainable grazing management in rangelands. Agriculture, Ecosystems & Environment, 283, 106561.

Eyüpoğlu, F. (1999). Fertility status of Turkish soils. Soil and Fertiliser Research Institute.

FAO. (2023). FAOSTAT: Land cover dataset. https://www.fao.org/faostat

Francoeur, R. B. (2013). Could sequential residual centering resolve low sensitivity in moderated regression? Open Journal of Statistics, 3, 24–44. https://doi.org/10.4236/ojs.2013.36A004

Gintzburger, G., Le Houérou, H. N., & Saidi, S. (2006). Near East–West Asia and semiarid rangelands. Sécheresse, 17, 152–168.

Gökkuş, A. (2018). An evaluation of our pastures. TÜRKTOB Dergisi, 25, 6–8.

Gujarati, D. N. (2011). Econometrics by example. Palgrave Macmillan.

Gürel, F. (2023). Effects of breeding practices and fertilisation on vegetation in barren pasture. Turkish Journal of Range and Forage Science, 4(2), 101–107. https://doi.org/10.51801/turkjrfs.1354522

He, M., & Dijkstra, F. A. (2014). Drought effect on plant nitrogen and phosphorus. New Phytologist, 204(4), 924–931. https://doi.org/10.1111/nph.12952

Heady, E. O., & Dillon, J. (1961). Agricultural production functions. Iowa State University Press.

Holechek, J. L., Geli, H. M. E., Cibils, A. F., & Sawalhah, M. N. (2020). Climate change and rangelands. Sustainability, 12(12), 4942. https://doi.org/10.3390/su12124942

Kara, A., Dumlu, E. S., Uzun, M., & Çakal, S. (2019). Twofold excessive utilisation rate threatens public rangelands. International Journal of Agriculture, Environment and Food Sciences, 3(3), 155–161. https://doi.org/10.31015/jaefs.2019.3.7

Karagölge, C. (2001). Agricultural management. Atatürk University Publications.

Kılıç, S., & Çınar, S. (2021). Effects of fertilizer applications on pasture yield and quality. Manas Journal of Agriculture, Veterinary and Life Sciences, 11(1), 67–75.

Koç, A., Gökkuş, A., & Altın, M. (2003b). Comparison of the worldwide used methods in the definition of range condition and a suggestion for Turkey. In Proceedings of the 5th Field Crops Congress of Turkey (pp. 36–42), 13–17 October 2003, Diyarbakır, Türkiye.

Koç, A., Güven, M., Çomaklı, B., Menteşe, Ö., & Bakoğlu, A. (2003a). Effects of nitrogen and phosphorus fertilization on grass yield and botanical composition of eastern Anatolian high-altitude rangelands. In Proceedings of the 5th Turkish Field Crops Congress (pp. 276–280), 13–17 October 2003, Diyarbakır, Türkiye.

Mariotte, P., Cresswell, T., Johansen, M. P., Harrison, J. J., Keitel, C., & Dijkstra, F. A. (2020). Plant uptake of nitrogen and phosphorus among grassland species affected by drought along a soil available phosphorus gradient. Plant and Soil, 448, 121–132. https://doi.org/10.1007/s11104-019-04407-0

Mermer, A., Tahtacıoğlu, L., Avcı, M., & Güveli, S. (1996). Effect of nitrogen and phosphorus fertilisation on grass yield of natural pastures in Eastern Anatolia region. In Proceedings of the 3rd Turkish Meadow–Pasture and Forage Crops Congress (pp. 137–145), 17–19 June 1996, Erzurum, Türkiye.

North Dakota State University. (1970). Native rangeland improvement studies (Research report). https://www.ndsu.edu/agriculture/ag-hub/publications/native-rangeland-improvement-studies

Notes for Ag. (2022). Precipitation, relative humidity, and wind effects on crop growth. https://notesforag.com/precipitation-relative-humidity-wind-effects/

National Research Council. (1999). Perspectives on biodiversity: Valuing its role in an ever-changing world. National Academy Press.

Olson, K. D. (2011). Economics of farm management in a global setting. John Wiley & Sons.

Pardini, A. (2009). Rangeland management. In F. Gherardi, C. Corti, & M. Gualtieri (Eds.), Biodiversity, conservation and habitat management (pp. 236–260). EOLSS Publishers.

Polat, C., Yıldız, M., & Demir, S. (2007). Effects of nitrogen and phosphorus levels on forage yield and quality in semi-arid rangelands. Journal of Plant Nutrition, 30(8), 1283–1295.

Polat, T., Bükün, B., & Okant, M. (2007). Dose response effect of nitrogen and phosphorus on forage quality, yield and economic return of rangelands. Pakistan Journal of Botany, 39(3), 807–816.

Rehber, R. (1999). Agricultural valuation and expertise. Vipaş.

Schacht, W. H., & Reece, P. E. (2009). Impact of livestock grazing on extensively managed grazing lands. In R. W. McDowell (Ed.), Environmental impact of pasture-based farming. CAB International.

Schleuss, P. M., Widdig, M., Heintz-Buschart, A., Kirkman, K., & Spohn, M. (2020). Interactions of nitrogen and phosphorus cycling promote P acquisition and explain synergistic plant-growth responses. Ecology, 101(5), e03003. https://doi.org/10.1002/ecy.3003

Spohn, M., & Kuzyakov, Y. (2025). Long-term nutrient interactions: Nitrogen-driven phosphorus acquisition in low-input ecosystems. Nutrient Cycling in Agroecosystems, 115(2), 155–170.

StataCorp. (2015). Stata statistical software: Release 14. StataCorp LLC.

Staub, J., Chatterton, J., Bushman, S., Johnson, D., Jones, T., Larson, S., Robins, J., & Monaco, T. (2016). A history of plant improvement by the USDA-ARS Forage and Range Research Laboratory for rehabilitation of degraded western US rangelands. Rangelands, 38(4), 233–240. https://doi.org/10.1016/j.rala.2016.08.004

Torrell, L. A., Rimbey, N. R., Tanaka, J. A., Taylor, D. T., & Wulfhorst, J. D. (2014). Ranch level economic impact analysis for public lands: A

guide to methods, issues, and applications. Journal of Rangeland Applications, 1, 1–13.

Torres-Reyna, O. (2007). Panel data analysis: Fixed and random effects using Stata (v. 4.2). Princeton University. https://www.princeton.edu/~otorres/Panel101.pdf

Turkish Statistical Institute (TURKSTAT). (2024a). Agricultural land and forest area, 1988–2024. https://data.tuik.gov.tr/

Turkish Statistical Institute (TURKSTAT). (2024b). Livestock statistics: Number of livestock. https://biruni.tuik.gov.tr/medas/?kn=101&locale=tr

Turkish Statistical Institute (TURKSTAT). (2024c). Chemical fertiliser use, 2009–2024. https://data.tuik.gov.tr/

Uslu, Ö. S., Yoldaş, N., Demir, Z., & Kafkas, B. (2021). Effects of nitrogen fertilization on yield, quality and botanical composition of a pasture in Kahramanmaraş, Türkiye. Manas Journal of Agriculture, Veterinary and Life Sciences, 11(1), 28–34.

Wang, R., Bicharanloo, B., Hou, E., Jiang, Y., & Dijkstra, F. A. (2022). Phosphorus supply increases nitrogen transformation rates and retention in soil: A global meta-analysis. Earth's Future, 10(3), e2021EF002479. https://doi.org/10.1029/2021EF002479

Williams, R. E., Allred, B. W., Reginald, M. D., & Paulsen, H. A. (1968). Conservation, development, and use of the world's rangelands. Journal of Range Management, 21, 355–360.

Zhao, R., Huang, X., & Chen, Y. (2023). Nitrogen–phosphorus interactions and alfalfa yield: A quadratic response to high P under arid conditions. Field Crops Research, 294, 108516.