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Alfalfa water productivity and yield gaps in the U.S. central Great Plains

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ABSTRACT

Context: Yield gap (Yg) analyses using farmer-reported yield and management data have been performed for a number of annual grain crops, but it lacks for perennial forages. The U.S. accounts for 21 % of the global alfalfa production with a large rainfed area located in the central Great Plains, serving as an interesting case-study for Yg in perennial forages. Most existing alfalfa Yg analyses quantified the magnitude of the Yg but failed to identify associated management practices to reduce it. Challenging this analysis, a systematic benchmark for alfalfa water productivity [WP, kg dry matter per mm evapotranspiration (ETc)] that allows for the quantification of Yg in farmer fields does not exist.

Objectives: Our objectives were to (i) benchmark alfalfa WP, (ii) quantify Yg in alfalfa farmer fields, and (iii) identify management opportunities to improve alfalfa yield.

Methods: We conducted a systematic review of literature and compiled a database on alfalfa yield and ETc (n = 68 papers and 1027 treatment means) from which a WP boundary function was derived. We collected management and yield data from 394 commercial rainfed alfalfa fields during 2016–2019 in central Kansas. We then used satellite imagery to define the growing season (and corresponding water supply) for each field. The boundary function was then used to calculate Yg of each field, and conditional inference trees (CIT) explored the impact of management practices associated with increased yield.

Results: Our boundary function suggested an alfalfa WP of 34 kg ha^{-1} mm^{-1}. Farmer-reported yield ranged from 0.9 to 19.0 Mg ha^{-1}, averaging 7.6 Mg ha^{-1}. Alfalfa water-limited yield potential (Yw) ranged from 11.1 to 23.2 Mg ha^{-1}, resulting in an average yield gap of 54–60 % of Yw. Row spacing, seeding rates, and management of phosphorus fertilizer were major agronomic practices explaining alfalfa yields in farmer fields, followed by surrogate variables as sowing season, stand age, and soil pH.

Conclusions: Our study provided the first systematic analysis estimating attainable alfalfa WP as function of ETc, suggesting that large alfalfa Yg exist in the U.S. central Great Plains. We also identified key agronomic practices associated with increased alfalfa yield.

Significance: The WP here derived can be used for future studies aiming at quantifying alfalfa Yg across the globe. This was an initial step in quantifying Yg and its associated causes at farmer fields, and we highlight limitations and future directions for perennial forages yield gap analyses.

1. Introduction

Alfalfa is a perennial forage legume of high nutritional value that is adapted to a broad range of environments (Diatta et al., 2021). Approximately 211 MMt of alfalfa are grown annually on about 32 M ha across the world for hay, haylage, silage, and pasture (Acharya et al., 2020; Research and Markets, 2020). Alfalfa is a perennial crop original from arid and semi-arid regions (Lesins, 1976) with a deep root system that continues to develop during periods of water deficit stress (Asseng and Hsiao, 2000; Jones and Zur, 1984), allowing it to cope with periods of mild droughts (Bauder et al., 1978; Carter and Sheaffer, 1983; J. Fan et al., 2016; J.W. Fan et al., 2016; Hayes et al., 2010). Still, forage

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production is often reduced under water-limited conditions (Carter and Sheaffer, 1983; Kilcher and Heinrichs, 1971). Management practices and breeding efforts have improved alfalfa yields by increasing transpiration (Johnson and Tieszen, 1994), though forage yield per unit transpiration (water productivity, WP) has remained constant (Tanner and Sinclair, 1983). Although the U.S. accounts for as much as 21 % of the area cultivated with alfalfa globally (Russelle, 2001), little effort has been made to understand the degree to which farmer yields are close to their yield potential as determined by climate and soil (van Ittersum et al., 2013).

In rainfed environments, seasonal water supply is often the major limiting factor for alfalfa forage yield (Jáuregui et al., 2021). A common framework to determine the attainable yield in water-limited environments consists of a boundary function relating crop yield with seasonal water supply or crop evapotranspiration (ETc) (French and Schultz, 1984). Following this approach, a linear function is fitted to the observations that define the upper limit of water-limited yield (Yw) over the range of seasonal water supply. For annual crops, the slope of the linear function determines WP and its intercept quantifies soil evaporation (French and Schultz, 1984). However, perennial crops are characterized by a lag-phase immediately after cutting and during initial regrowth, in which the proportion of solar radiation incident to the soil is high due to low leaf area index of the crop, increasing the potential for evaporative losses and modifying the linearity of the yield-ETc relationship (Kunrath et al., 2018). This lag phase requires consideration when developing the boundary function for perennial crops.

Boundary functions have been developed and used to benchmark WP, minimum evaporative losses, and to quantify the yield gap (Yg, i.e., the difference between the actual farmer yields [Ya] and the Yw for a given amount of water supply) for a number of annual crops, including wheat *(Triticum aestivum* L.) (French and Schultz, 1984; Sadras and Angus, 2006; Patrignani et al., 2014; Lollato et al., 2017), sunflower (*Helianthus annuus* L.) (Grassini et al., 2009), maize (*Zea mays* L.) (Grassini et al., 2009, 2011a; 2011b; Zhang et al., 2014), and soybean (*Glycine max* L. Merr.) (Grassini et al., 2015). Alfalfa WP has been quantified in individual studies as the relationship between shoot biomass and seasonal crop evapotranspiration, with WP often ranging between 11 and 21 kg ha^{-1} mm^{-1} (Bauder et al., 1978; Bolger and Matches, 1990; Sun et al., 2018). Lindenmayer et al. (2011) summarized a number of alfalfa studies in the U.S. to determine an average WP of 16 kg ha^{-1} mm^{-1}. However, these WP estimates are considerably below the theoretical maximum WP for alfalfa of 43 kg ha^{-1} mm^{-1} (or 32 kg ha^{-1} mm^{-1} excluding roots) at a vapor pressure deficit of 1 kPa (Tanner and Sinclair, 1983). While recent efforts related alfalfa yields to in-season precipitation (Baral et al., 2022; Feng et al., 2022), to our knowledge, there has been no explicit attempt to determine a WP boundary function for alfalfa using a systematic review of existing literature of crop yield and ETc.

One way to generate reliable estimates of alfalfa WP and Yg is using the forage yields reported by farmers under a wide range of soil and climate conditions. Farmer yields are usually well below the Yw due to incidence of other limiting and reducing factors (e.g., pest and fertility management, timing of operations, etc.) leading to yield gaps (van Ittersum et al., 2013). Efforts to quantify and understand alfalfa Yg around the globe have been limited. For example, previous studies for alfalfa grown in the US suggested Yg of 50–67 %, but neither directly accounted for the effect of seasonal water supply when quantifying attainable yields (Russelle, 2013), nor evaluated the influence of management practices (Baral et al., 2022). A Chinese study reported that current alfalfa forage yield at the farm level represents only 28 % of the potential forage yield (Wei et al., 2018). A study in dryland alfalfa in Iran used crop models to suggest an alfalfa forage Yg of 69 % of the Yw (Soltani et al., 2020). Recently, Jáuregui et al. (2021) quantified the Yg of rainfed alfalfa in the Argentinian Pampas as 27 % using crop modeling and data from variety performance experiments. While substantial efforts to understand Yg exist for annual crops (e.g. Grassini et al., 2011a, 2015; Jaenisch et al., 2019, 2021; Lollato et al., 2019; Rattalino Edreira et al., 2017), we are not aware of comprehensive studies aimed at diagnosing on-farm yield gaps and to better understand the underlying management factors explaining the gaps for pastures. This is particularly relevant for alfalfa grown in the U.S. central Great Plains as there is indication of a yield plateau during the past 30 years (Fig. 1). Measuring the current Yg and associated explanatory factors can help alfalfa growers to achieve further yield increases via improved agronomic management.

Our overarching objective was to determine the magnitude and leading causes of yield gaps in commercial alfalfa fields in Kansas, U.S., as this area accounts for ca., 38 % of alfalfa production in the U.S. central Great Plains and ca., 5 % of U.S. alfalfa production. To do so, we first had to establish a boundary function to benchmark on-farm alfalfa yields against seasonal crop evapotranspiration, which required a comprehensive synthesis of existing literature. Thus, our specific objectives were to (i) develop a boundary function of alfalfa yield-ETc relation using data from published field studies in a literature synthesis, (ii) use this boundary function to estimate yield gaps in commercial farmer fields, and (iii) identify management practices reflecting opportunities to increase forage yields and narrow forage yield gaps.

2. Materials and methods

2.1. Benchmarking alfalfa water productivity: A literature synthesis

A database of alfalfa forage yield and crop ETc was synthesized using published data from studies that represented a wide diversity of climates and growing conditions. Two systematic literature searches built the database: First, Google Scholar was searched six times for articles containing in their title or keywords the terms "Alfalfa + evapotranspiration", "*Medicago sativa* + evapotranspiration", "Lucerne + evapotranspiration", "Alfalfa + water use", "*Medicago sativa* + water use", and "Lucerne + water use" (accessed on July 2021). Next, the Scopus database was searched for articles which contained in their title, abstract, or keywords, the terms "alfalfa" or "lucerne" or "Medicago sativa", and "water productivity" or "water use" or "evapotranspiration" (accessed on July 2022). Both searchers restricted publication date for 1990 or later. All papers were downloaded and screened for minimum criteria for inclusion in the final database:

(i) Experiments were conducted under field conditions, disregarding simulation exercises, watershed-level analyses, and controlled-environment studies;

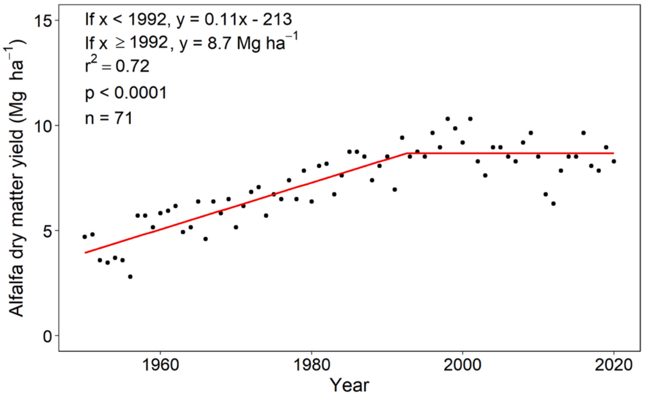

Fig. 1. Timeline of alfalfa dry matter yields in Kansas during the 1950–2020 period. Data were obtained from the USDA National Agricultural Statistics Service. The linear-plateau relationship between alfalfa yield and year (red line) and its statistics are also shown.

(ii) Experiments reported measured forage yield and ETc or crop water use by environment (i.e., not aggregated across environments); and

(iii) Experimental location and crop season were reported

Our systematic review of literature initially retrieved 483 manuscripts from both databases combined, from which 68 met the minimum criteria established above. Studies were mostly performed in China ($n = 27$), U.S. ($n = 11$), and Australia ($n = 9$), with the remaining studies conducted in Spain ($n = 3$), Argentina, Austria, Canada, New Zealand, Turkey ($n = 2$ each), France, India, Iran, Romania, Saudi Arabia, South Africa, and Tasmania ($n = 1$ each) (Table 1).(Table 2).

Data were extracted from tables and, when necessary, from figures using Web Plot Digitizer (https://automeris.io/WebPlotDigitizer/). From the database above, three manuscripts (i.e., Lindenmayer et al., 2011; Logsdon et al., 2019; and Minhua et al., 2022) were previous meta-analyses including papers published in language other than English. To avoid including these data into model development, we arbitrarily separated this subset for independent model validation (see below). The final database was composed of 791 alfalfa yield-ETc treatment means used for model development and 236 treatment means used for model validation.

The boundary function was obtained through linear quantile regression using alfalfa forage yield plotted as function of crop ETc (Koenker and Bassett, 1978). Here, the range in which alfalfa yield was responsive to increased water supply (i.e., from 38 mm to 600 mm) was split into 10 equally spaced intervals and a linear regression was fitted using the 95th percentile of each interval. To account for potential non-linearity in yield-ETc relation in alfalfa due the lag-phase immediately after cutting during each regrowth period, we tested for the significance of the quadratic term in the regression (Kunrath et al., 2018). As the quadratic term was not significant (data not shown), the slope of the linear equation was used to represent the attainable alfalfa WP (kg ha^{-1} mm^{-1}) and the x-intercept was used to provide a coarse estimate of minimum soil evaporative losses (mm). This model was validated against the dataset composed by the three alfalfa WP meta-analyses not used for model development ($n = 236$).

2.2. On-farm yield and management practices

Rainfed alfalfa grown in central Kansas was our case study for the on-farm survey. The typical climate conditions and soils in this region have been detailed elsewhere (Lollato et al., 2017, 2020(Sciarresi et al., 2019)), but briefly, annual precipitation ranges from ca. 450 mm in the west to 1100 mm in the east, and soils are typically characterized by a mollic epipedon. Ranking seventh in the U.S. for alfalfa hay production, Kansas produces approximately 2.3 MMt of alfalfa on ca. 100,000 ha (USDA-NASS, 2019) and has had severe yield stagnation since 1992 (Fig. 1).

Data were collected from 54 farmers via e-mail, phone, or in-person interviews. Survey data included field location, alfalfa forage yield, and 47 management practices that were either adopted at crop establishment or in individual years within the same field (Table 1). Data were collected exclusively from rainfed fields for the 2016, 2017, 2018, and 2019 crop seasons. Producers reported alfalfa hay yields in hay bales produced per year per field, in which case they were also asked to supply an average mass per hay bale and the field area. The accuracy of our yield data was double-checked by randomly contacting a subset of the original producers for a second, more detailed survey, where per bale weight was collected when available. Hay bales among the surveyed fields were either small square bales of ca. 22 kg (range: 21–23 kg), or large round bales of ca. 771 kg (range: 753–789 kg). Moisture content was not available from each field, and yields were assumed to be reported at 15 % moisture basis as there are mechanical problems associated with bailing alfalfa with < 13 % moisture (i.e., shattering), and molding problems associated with bailing alfalfa with > 17 % moisture. Yields were corrected to a dry matter basis. The resulting database represented 394 field-years originating from 139 individual fields (Fig. 2).

Soil available water holding capacity (AWHC), soil textural class, and soil pH were obtained for the 0–20 and 20–180 cm depths for each field from the USDA Web Soil Survey Geodatabase (USDA-NASS, 2015) using the geographic coordinates provided by the farmer. The upper 180 cm is sufficient to represent alfalfa rooting depth (J. Fan et al., 2016). If a field had more than one soil series, the AWHC and the soil textural class were area-weighted based on the percent of each soil series. Likewise, weighted AWHC and soil textures described the full soil profile.

2.3. On-farm growing season determination

The alfalfa growing season for each year (i.e., 2016–2019) was defined using time series of the enhanced vegetation index (EVI) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites. We integrated the 16-day EVI products at 250-meter spatial resolution from the Terra (MOD13Q1.061) and Aqua (MYD13Q1.061) satellites. Time series of EVI data were only retrieved for surveyed fields with an area ≥ 6.3 ha. Since the thermal and precipitation regimes of each year condition alfalfa growth and development, the start and end of the growing season were defined considering all fields in the survey for a given year. The beginning of the growing season was identified as two weeks prior the onset of rapid growth conditions computed as the highest growth rate in EVI in the first 75 days of the year (Fig. 3). The selection of the first 75 days was an arbitrary, but reasonable choice that captured alfalfa regrowth for most fields in our survey. Two variables determined the end of the growing season: it occurred four to six weeks prior the date in which minimum air temperature was equal to -2.8 °C, and immediately after the last EVI peak of the season (Fig. 3). The -2.8 °C is a threshold below which ice forms in alfalfa tissue (Sprague, 1955; Nath and Fisher, 1971; McKenzie and McLean, 1982), and our selection of four to six weeks prior to the first fall freeze is supported by previous research and local alfalfa recommendations in the region about the last alfalfa cutting in the fall (Shroyer et al., 1998).

For each field and growing season, we also retrieved daily weather data including growing season liquid precipitation, minimum air temperature, maximum air temperature, alfalfa reference evapotranspiration, and incident solar radiation from the Gridded Surface Meteorological (GRIDMET) dataset at ~4-km spatial resolution (Abatzoglou, 2012). This dataset is compiled by the University of Idaho and blends spatial data from Parameter-elevation Regressions on Independent Slopes Model (PRISM) and from the National Land Data Assimilation System (NLDAS). In addition, estimated alfalfa ETc was obtained for all fields with an area ≥ 25 ha ($n = 168$) from the MODIS Evapotranspiration/Latent Heat Flux product (MOD16A2, version 6) at 500-meter spatial resolution. All gridded and remote sensing data were retrieved using the Google Earth Engine platform.

2.4. Yield gap and on-farm water productivity analysis

To ensure that the maximum alfalfa yields reported by farmers were within the range of alfalfa yields measured in the region, we collected data from regional alfalfa variety performance trials conducted in Kansas and in Oklahoma during the 1998 – 2015 period ($n = 73$). Here, we screened each variety trial report (available at https://www.agronomy.k-state.edu/outreach-and-services/crop-performance-tests/wheat/ and http://croptrials.okstate.edu/alfalfa/, accessed July 2022) and selected the highest yielding variety at each given trial (Supplemental Table 1). Alfalfa dry matter yield was plotted against growing season precipitation during the growing season (day of year 50-275) which was retrieved from GRIDMET.

For each field-year included in the survey, alfalfa water-limited yield

Table 1
Manuscripts included in the alfalfa water productivity database. Manuscripts are ordered from lowest to highest maximum water productivity.

Man. no.	Reference	Country	Exp. year		n	Crop ET		Dry matter yield		Water productivity	
			Min.	Max.		Min. (mm)	Max. (mm)	Min. (kg ha^{-1})	Max. (kg ha^{-1})	Min. (kg ha^{-1} mm^{-1})	Max. (kg ha^{-1} mm^{-1})
1	Zhang et al. (2005)	Australia	2001	2003	3	142	205	760	1210	3.7	8.5
2	Al-Gaadi et al. (2017)	Saudi Arabia	2013	2014	2	415	2016	3582	18,271	8.6	9.1
3	Shi et al. (2020)	China	2016	2016	5	414	606	2522	4955	5.8	9.1
4	Benli et al. (2006)	Turkey	1995	1997	3	1161	1557	9200	16,700	5.4	10.0
5	Bali et al. (2001)	US	1996	1998	3	1109	1339	15,080	23,960	2.0	10.0
6	Rogers et al. (2016)	Australia	2010	2014	45	350	1470	1400	17,700	3.3	10.4
7	Brejea et al. (2010)	Romania	2007	2009	6	468	1034	3510	9830	7.1	11.1
8	Bell et al. (2012)	Australia	2009	2010	6	400	720	800	7200	7.9	11.3
9	Longsdon et al. (2019)	US	2017	2017	15	196	1200	2611	20,979	3.9	13.8
10	Singh et al. (2007)	India	1998	2005	1	642	642	8950	8950	13.9	13.9
11	Kuslu et al. (2010)	Turkey	2005	2006	12	188	688	1687	10,239	8.7	14.9
12	Pembleton et al. (2011)	Tasmania	2007	2008	8	794	1049	7810	15,740	9.2	15.9
13	J.W. Fan et al. (2016); J. Fan et al. (2016)	China	2011	2014	48	248	434	1290	5974	4.0	16.6
14	Dunin et al. (2001)	Australia	1995	1997	5	194	406	1500	7000	6.7	17.1
15	Lamm et al. (2012)	US	2005	2007	9	742	1069	19,800	22,500	7.1	17.2
16	Sanden et al. (2008)	USA	2006	2007	4	262	330	3970	5890	14.3	17.8
17	Klocke et al. (2013)	US	2007	2011	30	222	1137	500	20,400	13.6	17.9
18	Jun et al. (2014)	China	2009	2012	12	387	552	5374	7302	10.2	18.4
19	Sim and Moot (2019)	New Zealand	2011	2011	3	358	374	5900	6800	16.3	18.9
20	Murphy et al. (2022)	Australia	2015	2018	4	316	886	2842	16,913	3.9	19.1
21	Attram et al. (2016)	Canada	2012	2013	24	517	1038	4710	12,420	8.3	19.3
22	Stirzaker et al. (2017)	South Africa	–	–	3	453	537	9010	9530	17.7	19.9
23	Hirth et al. (2001)	Australia	1994	1999	10	341	696	3070	11,630	2.3	20.3
24	Jia et al. (2006a), (2006b)	China	2001	2003	15	213	421	535	6631	2.3	20.3
25	Hou et al. (2021)	China	2017	2018	2	595	617	9105	12,551	15.3	20.3
26	Ayars et al. (2009)	Spain	2005	2006	2	580	633	10,579	13,201	18.2	20.9
27	Jia et al. (2009)	China	2001	2005	10	38	420	624	6932	2.9	22.0
28	Carter et al. (2013)	USA	2012	2012	4	191	737	3900	15,293	20.2	22.4
29	Cavero et al. (2017)	Spain	2012	2014	18	511	1057	4430	21,690	8.7	22.6
30	Wang et al. (2018)	China	2015	2016	12	44	479	1012	9473	5.1	23.1
31	Pietsch et al. (2007)	Austria	2000	2001	2	332	429	5980	9940	18.0	23.2
32	Dardanelli and Collino (2002)	Argentina	1994	1997	16	564	965	9325	19,866	16.5	23.3
33	Ojeda et al. (2018)	Argentina	2013	2014	2	700	801	16,236	17,048	20.3	24.4
34	Lindenmayer et al. (2011)	US	–	–	176	196	1898	386	25,419	1.0	25.1
35	Wang et al. (2021a), (2021b)	China	2017	2018	8	422	881	8189	13,698	15.3	25.2
36	Jia et al. (2006a), (2006b)	China	2001	2003	5	1140	1204	6134	12,004	10.5	25.4
37	Li et al. (2017)	China	2014	2015	6	399	626	12,000	13,700	4.1	25.5
38	Wagle et al. (2019)	USA	2016	2017	2	373	440	7400	9670	16.8	25.9
39	Cavero et al. (2016)	Spain	2012	2014	12	802	891	15,549	21,992	17.7	25.9
40	Jefferson and Cutforth (2005)	Canada	1993	1998	6	123	311	2010	8080	16.3	26.0
41	Wang et al. (2022a), (2022b)	China	2018	2020	15	374	486	5023	16,491	19.3	26.7
42	(Mak-Mensah et al., 2021)	China	2020	2020	6	213	391	3018	9612	11.8	27.1
43	Moghaddam et al. (2013)	Austria	2007	2008	18	525	537	9600	14,900	18.2	27.9
44	Li and Su (2017)	China	2014	2015	8	344	867	9607	18,964	21.9	28.2
45	McCaskill et al. (2016)	Australia	2011	2012	2	138	330	2940	9540	21.3	28.9
46	Zhang et al. (2021a), (2021b)	China	2016	2017	16	151	452	4169	6298	12.3	29.8
47	Murray-Cawte (2013)	Australia	2012	2013	11	161	669	2303	18,776	12.5	30.0
48	Li et al. (2015)	China	2010	2011	24	187	322	2580	9076	21.7	30.1
49	Wang et al. (2015)	China	2012	2013	20	196	1898	386	25,419	2.3	30.6
50	Minhua et al. (2022)	China	–	–	45	207	1379	535	22,000	13.5	30.9
51	Sim (2014)	New Zealand	2011	2011	20	47	628	724	18,137	15.4	31.3
52	Lenssen et al. (2010)	US	2002	2006	5	142	339	1700	8300	9.9	32.6
53	Kunrath et al. (2018)	France	1982	1983	4	178	375	4022	10,362	22.6	32.8
54	Meng and Mao (2010)	China	–	–	3	391	533	10,175	17,561	26.1	33.0
55	Wang et al. (2021a), (2021b)	China	2006	2017	12	251	439	5383	11,222	18.7	33.5
56	Sun et al. (2018)	China	2014	2016	3	364	618	5610	13,020	9.1	34.1
57	Lindenmayer et al. (2008)	USA	2006	2007	8	254	874	8800	19,100	21.9	34.6
58	Scott and Sudmeyer (1993)	Australia	1986	1988	3	244	322	800	2800	1.0	34.9
59	Zhang et al. (2021a), (2021b)	China	2017	2019	24	376	1336	10,860	19,860	14.1	35.0
60	Qiu et al. (2021)	China	2016	2017	24	148	289	1860	7730	10.3	35.7
61	Garcia y Garcia and Strock, 2018	US	2013	2015	6	607	690	6947	16,750	9.8	35.9
62	Cui et al. (2018)	China	2014	2015	4	103	133	5097	5413	9.3	37.0
63	(Sun and Li, 2019)	China	2014	2017	4	355	606	5610	17,090	13.2	37.2
64	(Guan et al., 2013)	China	2004	2010	7	370	746	2300	22,200	6.2	37.8
65	Wang et al. (2022a), (2022b)	China	2012	2016	50	251	808	2982	12,123	6.1	38.5
66	Shen et al. (2009)	China	2002	2004	5	78	497	500	12,900	4.0	40.8
67	Gu et al. (2018)	China	2011	2016	48	72	516	70	14,845	0.3	42.7
68	Montazar and Sadeghi (2008)	Iran	–	–	73	102	291	2005	4263	38.3	52.8

Table 2
List of variables collected from commercial rainfed alfalfa fields in central Kansas (U.S.) during four crop seasons (2016–2019).

Parameters	Variables requested	Information provided
Field-specific information	Field coordinates	Latitude, longitude
	Field size	ha
	Grazing	Yes/no (if yes, duration of grazing)
	Cultivar name	Brand of seed
	Glyphosate resistant	Yes/no
	Low-lignin	Yes/no
	Sowing date	Month/year
	Seed treatment	Yes/no
	Seed inoculant	Yes/no
	Row spacing	cm
	Seeding rate	kg seed per ha
	Tillage method	No-till/minimum till/ conventional till
	In-furrow fertilizer	Yes/no
	Lime	Yes/no
	Previous crop	Crop species name
	Companion crop	Yes/no (if yes, crop species name)
Year-specific information	Fertilizer P, K, S, Bo, Zn, manure	
	Source	Source name
	Rate	kg nutrient ha^{-1}
	Timing	Month
	Method	Application method type
	Fungicide	Yes/no
	Insecticide	Yes/no
	Herbicide	Yes/no
	Maturity stage at cutting	Bud or early/mid/late bloom
	Crop yield	Mg ha^{-1}
	Prevalent pests/diseases	Pest species name
	Other issues/events that could affect yield	Issue/event description

potential (Yw, kg ha^{-1}) was estimated using the boundary function derived from the literature synthesis, in which the slope represents that attainable WP (kg ha^{-1} mm^{-1}) and the x-intercept provides as rough estimate of the minimum seasonal soil evaporation (mm):

$$\text{Yw} = \text{WP} \times (\text{water supply} - \text{soil evaporation}) \text{ if Yw} < 23{\cdot}2 \text{ Mg ha}^{-1} \qquad (1)$$

Water supply in Eq. (1) was computed either as alfalfa ETc (for the subset of fields for which satellite-derived alfalfa ETc was available; $n = 168$), and as growing season precipitation in an analysis involving all surveyed fields. In the latter, because estimates of minimum soil evaporation are usually lower against ETc as compared to precipitation (e.g., Grassini et al., 2009), evaporation was computed followed the findings of Baral et al. (2022) as 24 % of the mean growing season precipitation. The restriction of Yw to 23.2 Mg ha^{-1} was based on the maximum alfalfa yield measured in the regional variety trials, which was slightly greater than the maximum farmer-reported yield in our survey (19.1 Mg ha^{-1}) and was similar to the maximum yields in our literature analysis (Table 1). The Yg was then determined for each field-year as the difference between Yw and Ya, and on-farm WP was calculated for each field-year both the ratio of annual alfalfa yield over growing season ETc or cumulative precipitation.

2.5. Statistical analyses

Variation in producer-reported management practices, weather variables, and alfalfa yield were described using histograms and descriptive statistics. Conditional inference trees (CIT) were used to understand the interacting effect of weather, soils, and management on alfalfa dry matter yield (Mourtzinis et al., 2018; Jaenisch et al., 2021). For each tree, 43 explanatory variables were used, including 33 management variables (management variables with more than 40 % not reported observations were excluded), five soil variables (AWHC, soil pH, and sand, silt, and clay percentage), and five weather variables (cumulative growing season precipitation and solar radiation, and mean average, maximum, and minimum temperatures). Our objective with this analysis was to understand variable importance and conditional effects and not future prediction; therefore, we modeled the entire dataset rather than splitting it into training and testing subsets. To ensure adequate power and avoid overfitting, we ensured that each intermediate and terminal nodes had at least 20 % and 5 % of the

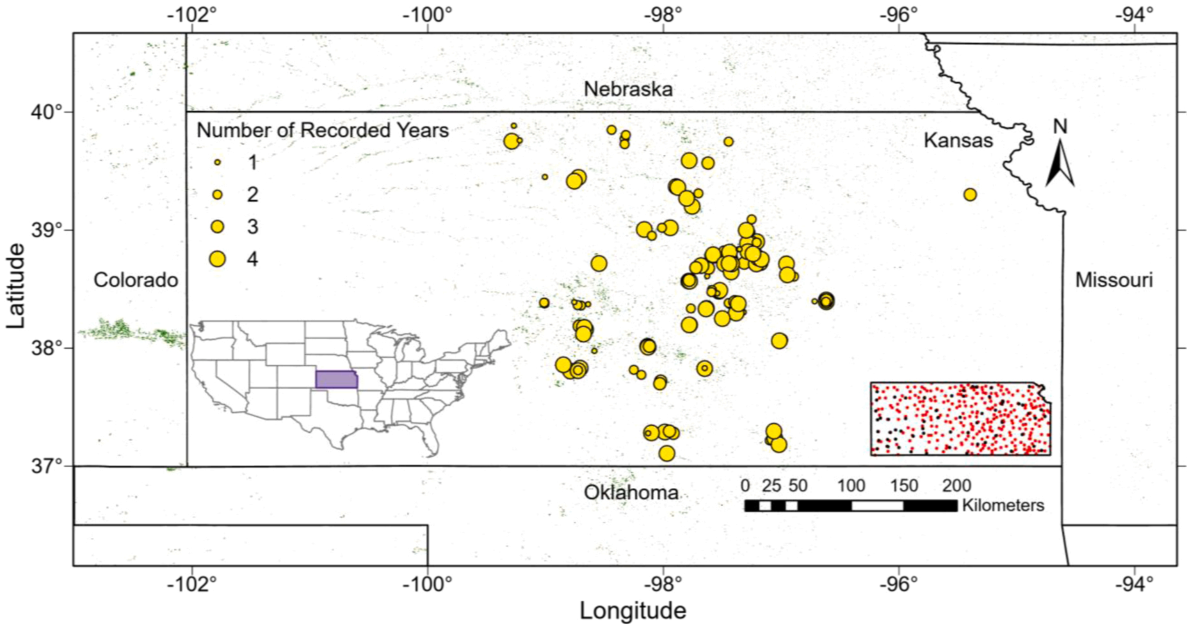

Fig. 2. Map of Kansas (U.S.) showing alfalfa planted area (green) and location of surveyed fields in 2016, 2017, 2019, and 2019 (yellow markers). Size of marker represents the number of years of data provided in the survey for each field. The green raster in the background represents alfalfa fields at 30-m spatial resolution obtained from the USDA Cropland Datalayer. Left inset shows location of Kansas within contiguous U.S., while right inset shows weather stations with available temperature and precipitation (red dots), and solar radiation and reference evapotranspiration (black dots) data for each surveyed field.

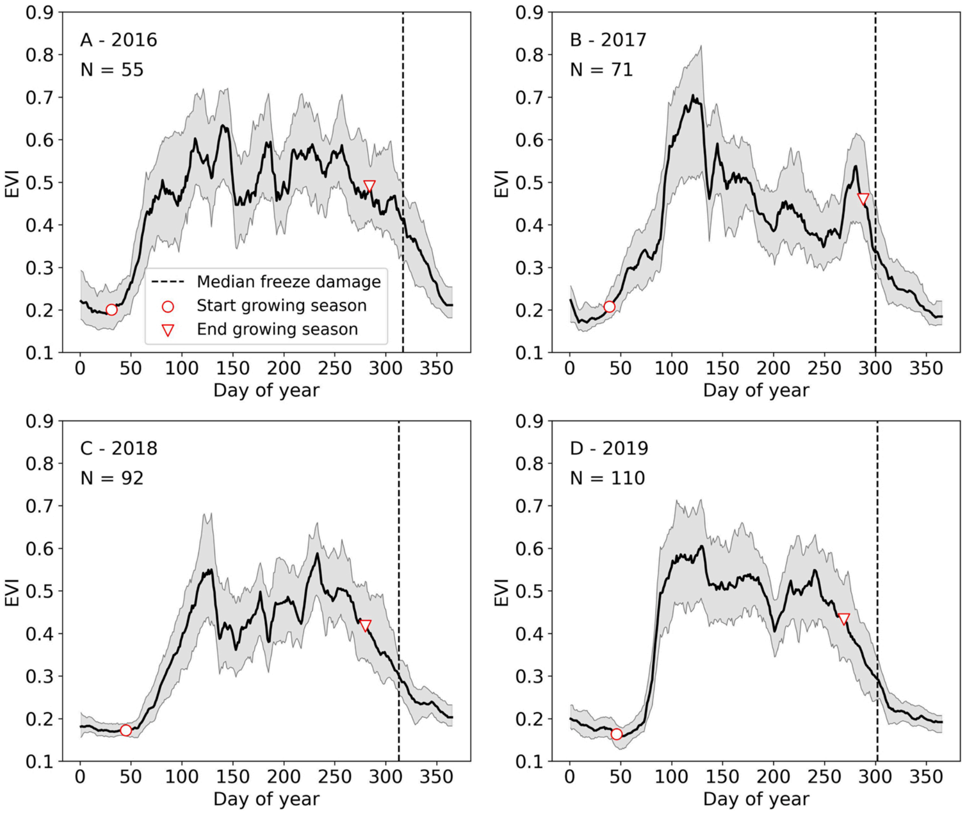

Fig. 3. Annual dynamics of enhanced vegetation index (EVI) for the surveyed fields obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites. Solid line shows the median EVI dynamics across fields and the grey area shows the interquartile range. Red markers denote the beginning and end dates of each growing season.

observations ($n = 80$ and 20 fields). We used the coefficient of determination (r^2) and root mean square error (RMSE) to evaluate the fit of the CITs. To assess correlated variables within the subset of data used in each split, we evaluated the next three surrogate splits of the final model to identify variables that result in a good approximation of the primary results in case data for these are missing (e.g., Lawes et al., 2021). The CIT were fit with function ctree from package partykit (Hothorn and Zeileis, 2015; Hothorn et al., 2006).

3. Results

3.1. Attainable alfalfa water productivity

Alfalfa yield retrieved from the literature synthesis used for model calibration ranged from 0.7 to 23.9 Mg ha^{-1} (mean: 8.3 Mg ha^{-1}) and alfalfa ETc ranged from 38 to 2016 mm (mean: 493 mm), resulting in an average WP of 18 kg ha^{-1} mm^{-1} and a range from 0.3 to 43 kg ha^{-1} mm^{-1} (Table 1, Fig. 4 A inset). A boundary function based on measured yields and ETc resulted in a slope of 34 ± 2 kg ha^{-1} mm^{-1} and an estimate of seasonal soil evaporation of 13 mm (Fig. 4 A). Alfalfa yield, ETc, and WP in the validation dataset ($n = 236$) ranged from 0.4 to 25.4 Mg ha^{-1}, from 183 to 1898 mm, and from 1 to 32 kg ha^{-1} mm^{-1} (Fig. 4B). The boundary function was robust against the validation dataset, as it bounded the majority (~99 %) of its data points (Fig. 4B).

3.2. Soil, weather, and management in alfalfa farmers' fields in Kansas

The soil in the majority of the surveyed fields had between 30 % and 50 % clay content, with sand and silt contents ranging from near null to 100 % (Fig. 5A). The corresponding AWHC in the 180 cm soil profile ranged from 123 to 404 mm (Fig. 5B). Soil pH in the 0–15 cm soil layer ranged from 5.2 to 8.5 (Fig. 5C). Growing season alfalfa ETc ranged from 340 to 811 mm (Fig. 5D), and precipitation ranged from 510 to 1384 mm (Fig. 5E). Growing season mean Tmin ranged from 8.9 to 13.3 °C (Fig. 5F) and Tmax ranged from 21.9 to 27.3 °C (Fig. 5G). Growing season solar radiation ranged from 4541 to 5171 MJ m^{-2} (data not shown).

Field size ranged from 0.6 to 105 ha (Fig. 6A), with corresponding alfalfa stand age averaging 3.3 years and ranging from less than one to ten years (Fig. 6B). Seeding rate ranged from 9 to 33.5 kg ha^{-1} (Fig. 6C), and most of the fields were sown in the fall (81 %) with fungicide and/or insecticide treated seed (84 %) and inoculated with rhizobium bacteria (92 %) (Table 3). Most producers followed conventional tillage (78 %). Only a few fields reported use of in-season foliar fungicides (1 %), low-lignin cultivars (2 %), companion crops (3 %), cattle grazing (10 %), and in-furrow fertilizer applications (17 %). Year-specific inputs such as phosphorus fertilizer (38.7 ± 1.5 kg ha^{-1}, 78 % frequency adoption), herbicides (8.66 ± 0.22 kg ha^{-1}, 66 % adoption), and insecticides (9.1 ± 0.2 kg ha^{-1}, 88 % adoption) were applied to most fields and years (Table 3, Fig. 6E). However, nutrients such as potassium (20.3 ± 1.9 kg ha^{-1}), sulfur (3.7 ± 0.4 kg ha^{-1}), and micronutrients like boron (0.14 ± 0.03 kg ha^{-1}) and zinc (0.3 ± 0.04 kg ha^{-1}), were only adopted in 6–40 % of the fields (Table 3, Fig. 6F-H). On average there were four cuts per season (53 % of surveyed fields), with 22 % of the fields had fewer cuts and about 25 % of fields were cut five times per season (Fig. 6D).

3.3. On-farm alfalfa yield gaps and water productivity

Alfalfa Ya averaged 7.6 Mg ha^{-1} and ranged from 0.8 to 19.1 Mg ha^{-1} across the surveyed fields (Figs. 7A, 7B). Maximum reported alfalfa yields in the farmer database was within the range of yields measured in alfalfa variety trials in the region (Fig. 7B) and was slightly below the 2016–2019 average USDA-NASS reported alfalfa average yield for

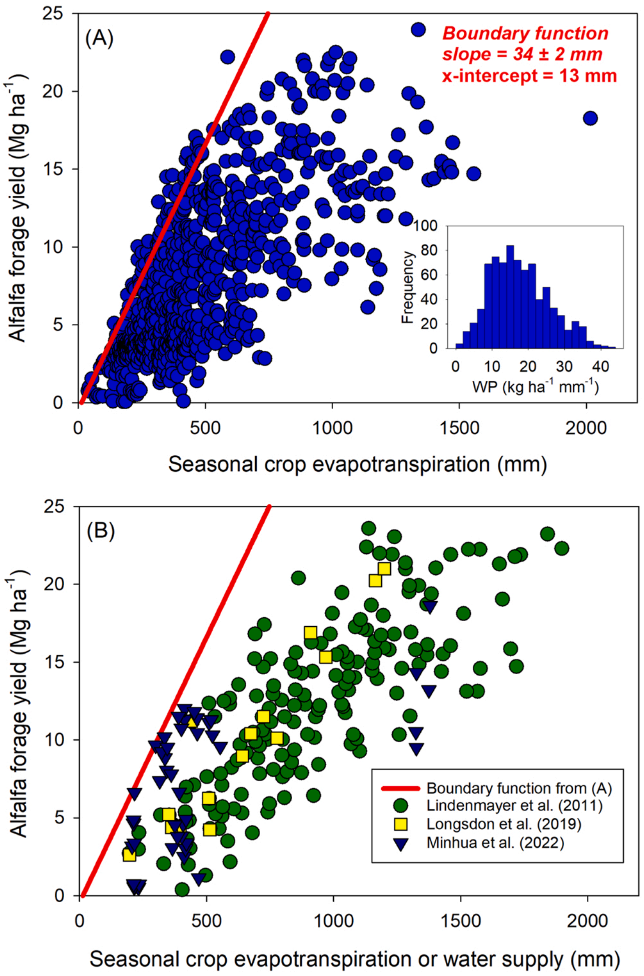

Fig. 4. (A) Relationship between literature-reported alfalfa yield and evapotranspiration (ETc). The red solid line represents the boundary function using the 95th percentile. Regression parameters (slope ± s.e. and x-intercept) are shown. Inset shows the water productivity (WP) distribution of the retrieved datapoints. **(B)** Validation of the boundary function against three independent alfalfa water productivity meta-analyses.

Kansas (8.6 Mg ha^{-1}), likely because we did not include the higher-yielding southwest portion of the state where alfalfa is mostly irrigated. Alfalfa Yw based on satellite-derived ETc ranged from 11.1 to 23.2 Mg ha^{-1} and averaged 16.6 Mg ha^{-1}, resulting in Yg ranging from nil up to 86 % of Yw and averaging 54 % across field-years (Fig. 7A). Precipitation-based Yw and Yg were slightly larger, averaging 19.5 Mg ha^{-1} and 60 %, respectively (Fig. 7B). Field-level alfalfa WP (yield per unit ETc) averaged 15 ± 0.4 kg ha^{-1} mm^{-1}, ranging from 5 to 35 kg ha^{-1} mm^{-1} (Fig. 7C); and yield per unit precipitation averaged 9.7 ± 0.2 kg ha^{-1} mm^{-1} and ranged from 1 to 28 kg ha^{-1} mm^{-1} (Fig. 7D).

3.4. Management, weather, and soil effects on alfalfa yield

Across all field-years, alfalfa yield was lowest in fields with one or two cuts per year and highest in fields with four or five cuts per year (Supplemental Fig. 1). Because the number of cuts per year can be either a consequence of greater yields requiring more frequent harvests, or a cause of greater yields due to reduced harvest losses, this variable was discarded from the CIT analyses. Fields sown in the fall had greater first-year yield than fields sown in the spring (9.4 vs. 7.4 Mg ha^{-1}), partially due to the potential for a greater number of cuts in the first year (3.9 versus 3.2) (data not shown).

The CIT explained 24 % of the alfalfa dry matter yield variability, with a RMSE of 2.8 Mg ha^{-1} (Fig. 8). The soil's AWHC was the most important factor determining alfalfa forage yield. Fields with AWHC > 354 mm yielded between 7.3 and 11.8 Mg ha^{-1}, and the highest yields were attained in fields that adopted row spacing narrower than 18 cm or broadcast seed. Fields that adopted row spacing wider than 18 cm yielded between 7.3 and 9.3 Mg ha^{-1}, depending on P fertilizer application method. Fields with AWHC ≤ 354 mm yielded between 5.6 and 8.0 Mg ha^{-1}, with fields receiving more than 908 mm precipitation resulting in the highest yields. Among fields receiving less than 908 mm of precipitation in season, either row spacing < 18 cm or seeding rate > 18 kg ha^{-1} in fields with row spacing wider than 18 cm associated with the highest yields.

Surrogate variables detected by the CIT explaining alfalfa yield for nodes 1 and 2 were mostly environmental variables (minimum and maximum temperatures, soil silt percentage, and solar radiation), with the exception of the incidence of insects and weeds as problems reported by growers. Meanwhile, management variables populated the surrogates for nodes 3, 5, 9, and 11, including phosphorus fertilizer management (presence of in-furrow fertilizer, and phosphorus application rate, method, source, and timing), stand age, soil pH, herbicide application, and farmer's cutting goal (Supplemental Table 2).

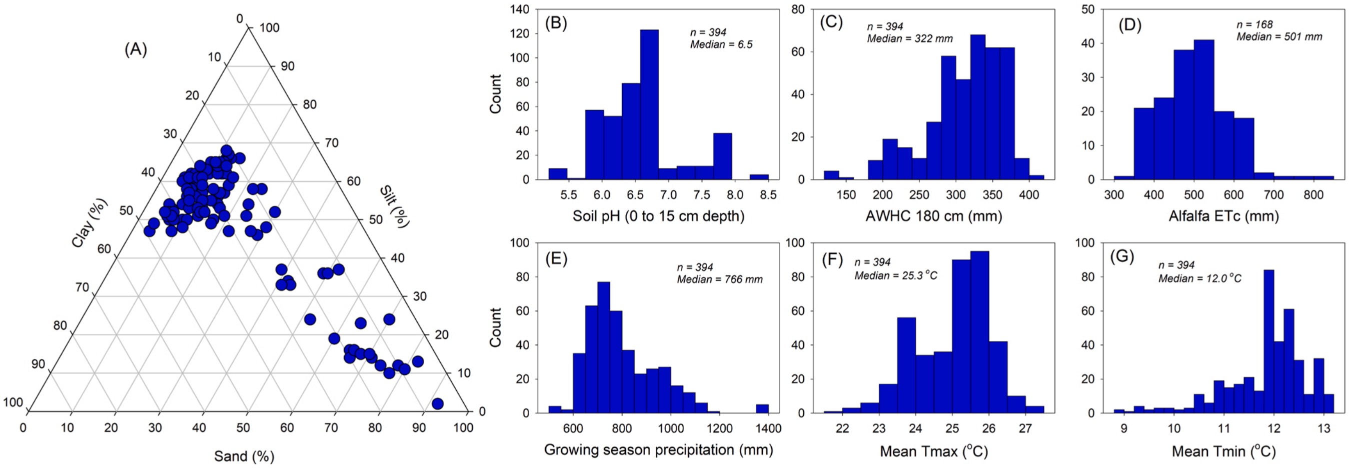

Fig. 5. Edaphic and climatic characteristics of the studied alfalfa field-years in Kansas: (A) soil textural ternary plot, and histograms of (B) soil pH in the upper 15 cm soil layer, (C) available water holding capacity in the 180 cm soil depth, and growing season (D) total alfalfa evapotranspiration (ETc) and (E) precipitation, and mean (F) maximum and (G) minimum temperatures.

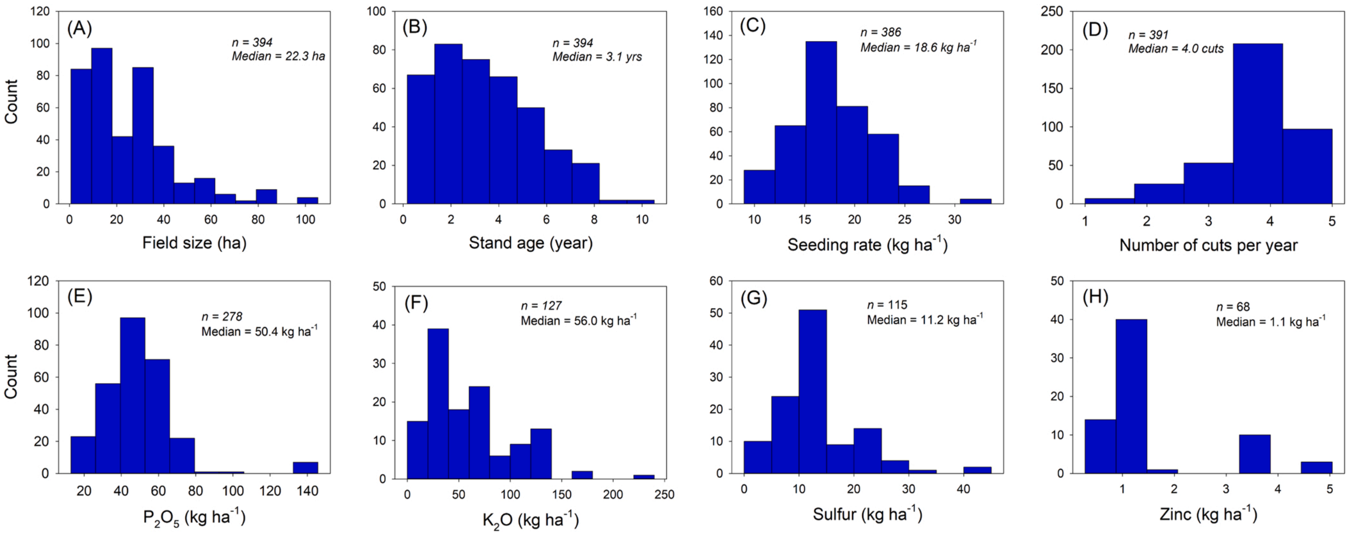

Fig. 6. Distributions field size (A), stand age (B), seeding rate (C), number of cuttings per year (D), and nutrient application rates (E-H) from producer-reported survey database of alfalfa fields in Kansas. Nutrient rates were calculated based on fertilizer composition and application rates and are only shown for fields receiving nutrient applications (the number of fields and the median nutrient rate for fields receiving application is indicated in each panel).

Table 3
Frequency of adoption of different management practices among the 394 alfalfa field-years surveyed in central Kansas during the 2016–2019 growing seasons.

Management	Frequency (%)
Grazing	10
Cultivar (Roundup Ready)	34
Cultivar (Low lignin)	2
Planting Season (Fall)	81
Seed Treatment (Fungicide/Insecticide)	84
Seed Inoculated	92
Tillage Method (Conventional tillage)	78
In-furrow Fertilizer	17
Lime	42
Companion Crop	3
Phosphorus	78
Potassium	40
Sulfur	32
Boron	6
Zinc	17
Fungicide	1
Insecticide	88
Herbicide	66

4. Discussion

A synthesis of published literature of alfalfa yield and ETc revealed the upper boundary of alfalfa water productivity and the lower boundary of alfalfa evaporative water losses on an annualized basis. This boundary was then used to quantify the water-limited yield and yield gaps of hundreds of surveyed farmer alfalfa fields in the U.S. central Great Plains, revealing management-by-environment interactions affecting alfalfa forage yield in this region. While yield gap analyses have been performed for many annual grain crops, forage yield gap work is at the very infancy (e.g., de Oliveira Silva et al., 2017; Martha Jr. et al., 2012; Strassburg et al., 2014), and this paper is an initial attempt to fill this substantial gap in knowledge about what are the yield gaps in forage crops and associated causes.

4.1. Alfalfa water productivity and yield gaps

An original contribution of the current work was to derive a WP benchmark for alfalfa against which researchers and producers can compare annualized alfalfa yields and quantify the magnitude of the Yg. The slope of the linear boundary between yield and ETc provided an estimate of the attainable WP (34 kg ha^{-1} mm^{-1} ha^{-1}), which was remarkably similar to the theoretical maximum WP for alfalfa shoot biomass of 32 kg ha^{-1} mm^{-1} (Tanner and Sinclair, 1983) and greater than most previously reported alfalfa WP (interquartile range of our literature review: 11–22 kg ha^{-1} mm^{-1}; inset of Fig. 3A). Our estimate of seasonal soil evaporation was low (13 mm), representing ca. 3 % of the total ETc (average: 493 mm). While this estimate is similar to previous estimates of the fraction of ETc represented by evaporation in alfalfa in a full canopy state (ca. 7 %; Wright, 1988), it is lower than that reported by previous research partitioning yearly alfalfa ETc where evaporation represented ca. 20–30 % of total yearly ETc (Wagle et al., 2019, 2020; Wright, 1988) or 24 % of the mean growing season precipitation (Baral et al., 2022). This discrepancy is likely due to the nature of the boundary function analysis, which evaluates only the most efficient points that minimize water losses (FAO and DWFI, 2015), especially when derived as function of crop ETc instead of water supply (e.g., Grassini et al., 2009).

We used growing season precipitation instead of annual precipitation because the majority (86 %) of the precipitation in this region falls during the growing season, resulting in limited winter recharge (average: 77 mm versus 816 mm average annual precipitation, data not shown) (Grassini et al., 2010). We note that using growing season rainfall ignores the water available to the crop at spring re-growth, so a key assumption here is that the amount of available soil water at spring re-growth and at the end of the growing season are similar. Nonetheless, this approach avoids assumptions and uncertainties in the estimation of AWHC and its simplicity may allow for a quicker adoption by farmers. Still, our CIT analysis showed that fields with large AWHC exhibited greater yields as compared with those with low AWHC (Fig. 8), suggesting that, for a given amount of seasonal rainfall, Yw may be influenced by the AWHC (although this might be confounded by other soil properties associated with AWHC). This agrees with other research where alfalfa Yw was impacted by the soil's AWHC (Jáuregui et al., 2021). Thus, future work could refine our approach to include the effect of AWHC in Yw estimates, which determines the capacity of soils to buffer against rain-free periods.

Using either growing season ETc or rainfall combined with benchmark WP, we quantified a wide range in Yg among the surveyed alfalfa fields. Average Yg represented 54–60 % of Yw and ranged from nil to 88 %, associating positively with Yw (r^2 0.28–0.42, $p < 0.001$, data not shown). Field-level WP also had a large ragend and was considerably

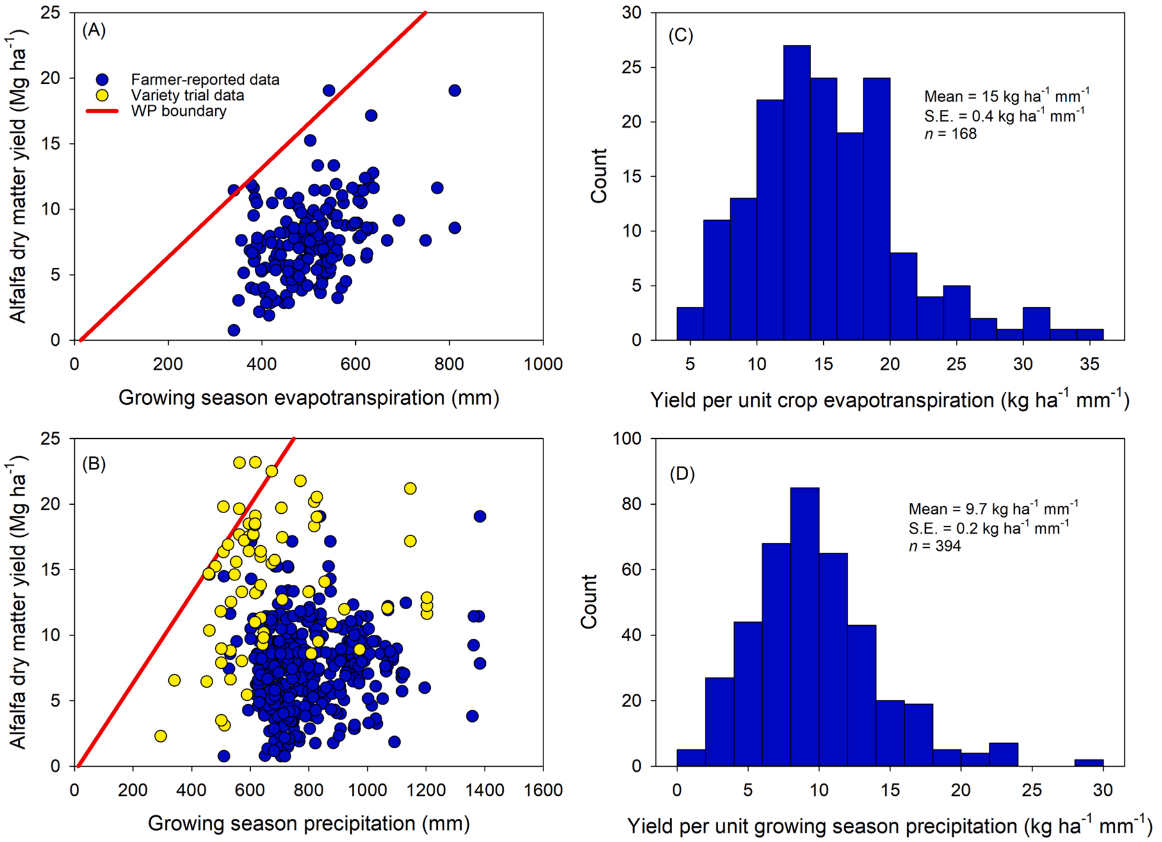

Fig. 7. Relationship between farmer-reported alfalfa yield and growing season (A) evapotranspiration (ETc) and (B) precipitation. Red boundary function and its linear coefficients are those developed and demonstrated in Fig. 4A. Alfalfa water productivity distribution among the surveyed commercial fields are shown on (C) alfalfa growing season ETc and (D) precipitation.

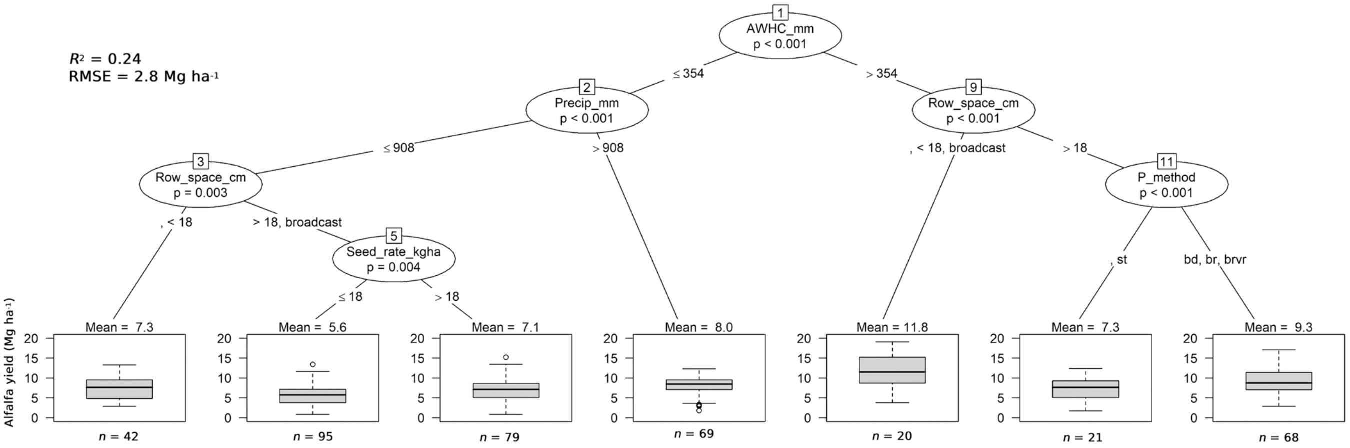

Fig. 8. Conditional inference tree of the effects of weather, soil, and management practices on alfalfa yield across 394 field-years surveyed in central Kansas, U.S, during the 2016–2019 growing seasons. Each boxplot represents the interquartile range (gray box), median (solid line), fifth and 95th percentiles (whiskers), and outliers (black circles). The number of observations (n) are shown. Acronyms: AWHC_mm, Available water holding capacity in the 180 cm soil profile (mm); row_space_cm, row spacing in cm; P_method; phosphorus application method (bd = banded, st = streamed, sp = sprayed, br = broadcast, brvr = broadcast variable rate); precip_mm, cumulative rainfall during the growing season (mm); and seed_rate_kgha, seeding rate (kg ha^{-1}).

below the attainable (15 vs. 34 kg ha^{-1} mm^{-1}). These wide ranges in Yg and WP are typical of rainfed cropping systems with large Yg (e.g., Jaenisch et al., 2021; Lawes et al., 2021), and larger Yg in seasons with higher Yw suggests that the current management adopted by alfalfa farmers has a larger opportunity cost in favorable seasons. Likewise, our average alfalfa Yg was remarkably similar to the Yg estimate from Russelle (2013) and from Baral et al. (2022) for the US (50–67 %). We note, however, that our analysis expand on that by Russelle (2013) because despite using a number of approaches (i.e., survey of crop consultants, alfalfa cultivar performance trials, official census of agriculture, and on-farm yields from 1970 to 1980 s), Russelle (2013) did not account for the effect of the weather – in particular, water supply – when quantifying attainable yields; and neither paper quantified the impacts of management practices on alfalfa yield. When compared to other alfalfa growing regions for which Yg estimates are available, the alfalfa Yg in Kansas seems to be similar to that of Iran (c.a., 69 %; Soltani et al., 2020), narrower than in China where Ya are only 28 % of Yw (Wei et al., 2018), and larger than in Argentina where current rainfed alfalfa forage yields are around 78 % of Yw (Jáuregui et al., 2021). These comparisons are made with caution as different methodologies were employed in each of the aforementioned studies, also highlighting the need for a more homogenous Yg estimation across studies (e.g., Rattalino Edreira et al., 2021).

4.2. *Alfalfa management for improved yield*

Reduced row spacing and increased seeding rate associated with higher yields (Fig. 8, Supplemental Table 2), likely due to a more uniform early-season coverage and better weed suppression (Redfearn et al., 2009), aligning with studies where decreased row spacing increased alfalfa canopy cover and its ability to compete for resources (Klapp, 1957; Soya et al., 1997; Acikgoz, 2001). This is also supported by the fact that fields reporting incidence of weeds (or the combination of weeds and insects)had lower yields than those reporting no issues. We note in passing that the most recurring weed problem reported by growers was *Amaranthus palmeri* and the most recurring insect pest was *Hypera postica* (data not shown). Seeding rate can impact alfalfa yield (Moline and Robison, 1971) through its influence on yield components (Stanisavljević et al., 2012) and on the retention of an adequate plant density after the establishment year (Hall et al., 2004). However, seeding rates can be excessive (Bradley et al., 2010; Moline and Robison, 1971; Hansen and Krueger, 1973), so further research on this topic is warranted. We also note in passing that the seed coating associated with alfalfa seed treatment can account for up to 20–30 % of alfalfa seed weight (Smith, 2009). When we adjusted for this variable, the CIT was nearly identical to that shown in Fig. 8, and therefore we acknowledge that seed rates may be slightly inflated but we did not use the adjusted seed rates to avoid assumptions regarding seed coating weight.

Application of phosphorus fertilizer, as well as its source, method, and timing of application, associated with alfalfa yield (Fig. 8, Supplemental Table 2). The importance of P for alfalfa production agrees with a recent meta-analysis suggesting increased alfalfa yields with increased soil available phosphorus (Feng et al., 2022) and with a comprehensive Yg review by Beza et al. (2017) that suggested fertilization practices were among the most important practices to reduce Yg of several crops. These results are also consistent with replicated studies where P application (and that of other nutrients) increased alfalfa dry matter yield (Berardo et al., 2007; Berg et al., 2005; Fontanetto et al., 2007, 2010; Jones and Sanderson, 1993; Malhi and Goerzen, 2010; Malhi, 2011; Sevilla and Agnusdei, 2016). The high rate of soil P removal by alfalfa (ca., 12–15 kg P_2O_5 per Mg ha^{-1} of alfalfa forage harvested; Lamond, 1998) also justifies the importance of P fertilization in improving alfalfa yields. Previous replicated trials support the importance of the method of application of P fertilizer in modulating the yield of alfalfa (Sheard et al., 1971; Goos et al., 1984) and of annual crops (Randall and Hoeft, 1988; Bailey and Grant, 1990). For instance, Malhi et al. (2001) observed that subsurface banding of P fertilizer resulted in greater alfalfa yield, P recovery, and net returns; however, the authors and others later noticed that subsurface banding of P into an established stand can damage the alfalfa's taproots and crown, resulting in inconsistent yield response (Leyshon, 1982; Malhi et al., 2004).

Additional surrogate variables that associated with alfalfa yield were stand age and soil pH (Supplemental Table 2). Alfalfa crops that were older than seven years yielded less than younger stands, which can be explained by reductions in alfalfa stand over time that are worsened by sub-optimal cutting and pest management regimes (Shroyer et al., 1998), irrigation (Neal et al., 2009), shallow water table (Berhongaray et al., 2019), and reductions on soil water storage and soil available phosphorus (Wang et al., 2021a, 2021b). Fields with soil pH > 7.0 also had greater yields than their lower pH counterparts, which can relate to greater alfalfa stand survival and to a more favorable environment to ensure nodule colonization by *Rhizobium spp.* bacteria that has an optimum soil pH of 6.5–7.0 (Peters et al., 2005).

4.3. *Limits of the current approach and future research*

Our study has a few limitations that future yield gap and water productivity analyses of alfalfa and other perennial crops can improve upon. One limitation of the current work is that alfalfa is a perennial crop and the boundary function approach was developed and used for annual crops (FAO and DWFI, 2015; and citations therein). We attempted to overcome this uncertainty by testing quadratic models that were not significant, suggesting that WP was constant rather than being lower in the lag phase immediately after each cut (Kunrath et al., 2018). Another perhaps more relevant issue associated with the perennial nature of alfalfa is that of with seasonal growth cycles impacting WP due to the different weather conditions experienced during each regrowth, in particular vapor pressure deficit (Kunrath et al., 2018) which is closely linked to WP (Passioura and Angus, 2010). While the mean of individual seasonal maximum WP reported by Kunrath et al. (2018) matched closely to our WP estimate (31 vs. 34 kg ha^{-1} mm^{-1}), their individual WP measures ranged from as low as 11 kg ha^{-1} mm^{-1} in the second regrowth of one of the studied years to 42.3 kg ha^{-1} mm^{-1} in the first regrowth of one of the studied years. Beyond the differences in vapor pressure deficit experienced in each cut cycle, the seasonality of alfalfa resource productivity also seems to be explained by variations regarding shoot-to-root dry matter allocation, resulting in greater radiation use efficiency under longer days in early summer as compared to shorter days in late summer and early fall (Thiébeau et al., 2011). This seasonally in radiation use efficiency is mirrored by water productivity (Kunrath et al., 2018). Evaporation estimates using this linear approach also seem to have a seasonal pattern, with lower evaporative losses after the first regrowth as compared to the second (Kunrath et al., 2018). These differences in evaporative losses can be partially explained by dynamics of alfalfa leaf area index development after cutting, as there are more axillary buds with tendency to sprout after cutting in the spring and early summer as compared to in late summer and fall (Gosse et al., 1988). Future work could potentially overcome the above uncertainties by evaluating on-farm alfalfa yield and management practices by regrowth rather than annualized.

Another limitation of the current study is associated with the nature of boundary functions, which do not account for the seasonality and size structure of precipitation (FAO and DWFI, 2015), or for non-growing season precipitation. This can be especially concerning in U.S. central Great Plains environments characterized by small individual precipitation events (Patrignani et al., 2014) that result in greater losses of water by soil evaporation, and greater interception by the crop canopy and standing residue (Sadras, 2003; Sadras and Rodriguez, 2007). Future work could overcome this uncertainty by using complex mechanistic crop simulation models to account for suboptimal precipitation distribution in the growing season and for non-growing season precipitation, although simpler boundary functions usually match those derived from crop simulation models involving numerous crop and soil parameters and daily weather variables (O'Leary and Connor, 1996; Angus and van Herwaarden, 2001; Grassini et al., 2009).

5. Conclusions

The synthesis of literature-reported alfalfa water productivity data and a survey of a one-of-a-kind database encompassing 394 commercial alfalfa fields in Kansas allowed us to benchmark alfalfa water productivity, as well as use this region as a case-study to estimate actual forage yields, water-limited forage yield, and forage yield gaps. These analyses also allowed for a quantification of the current level of adoption of management practices in commercial fields, as well as their interactions with soil and weather variables modulating alfalfa hay yields in Kansas. An average yield gap of 54–60 % suggests large room for yield improvement via agronomic management, and the most immediate practices that could apparently be improved included P management, row spacing, seeding rate, sowing date, soil pH, and termination of the stand prior to 7 years of age.

CRediT authorship contribution statement

K.P.F.: Data acquisition, Formal analysis, Investigation, Visualization, Writing – original draft, P.G.: Conceptualization, Methodology, Validation, Writing - review and editing, A.C.R.: Funding acquisition, Resources, Writing - review and editing, L.M.B: Formal analysis, Visualization, Writing - review and editing, L.P.R.: Data acquisition, Visualization, X.L.: Data acquisition, A.P.: Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources, Validation, Writing - review and editing, R.P.L.: Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources, Validation, Project management, Writing - review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2022.108728.

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