Final Report:
Irrigated Land Cover by Land Use in Colorado

Andrew Marx, PhD [1]

[1]Correspondence: marxaj@planetscapeai.com
30-Aug-24

Executive Summary

This research project used land use data and 2021 aerial imagery to estimate that there is 1,465 acres of non-functional irrigated turf in Denver County. Following a successful evaluation of the imagery classification algorithm (95% accurate), this study identified 13,124 total acres of irrigated turf within developed areas. Developed areas exclude airports, agricultural zones, and vacant/open spaces. Within this, 89% is functional turf (including Single Family Residential, Parks, Golf Courses, Multi-Family Residential, Education, Cemetery, Mixed, and Facilities), while 11% is non-functional turf (Transportation and Utility, Commercial and Industrial) (see Appendix C).

Additionally, this study provides the area of bushes/trees and impervious/other by land use as well as the number and area of pools in the study area (Section 3.2).

These findings highlight significant potential for a turf rebate program targeting SFR and MFR land uses, which account for 7,541 acres of the identified turf. It also finds that non-functional irrigated turf makes up a small, but not inconsequential area of the developed county for a rebate program (1,465 acres).

1. Introduction

This final report outlines the tasks completed during the pilot study aimed at supporting initiatives like the Colorado Water Plan and the State's Turf Replacement Program. The study's objective was to measure the extent of irrigated land within Denver City and County using multispectral imagery from the USDA National Agricultural Imagery Program (NAIP).

The full study was conducted across three tasks. The first and second tasks focused on producing a land cover analysis, aggregating land use categories, and assigning land cover amounts to parcel groups. The third task was a manual validation assessment to compare PSAI's completed land cover dataset with the City and County of Denver's land cover dataset.

2. Study Area

The boundary of Denver County[1] was clipped with 2023 US Census Populated Places[2] and the Denver Water service area[3] for the 155 square mile (4,321 million sqft) area study area (Figure 1).

3. Data and Analytic Approach

The analytic approach for this project was to combine two customized datasets to allow interactive determinations of NFT depending on land use categories.

3.1 Land Use Processing

Denver land use was collected from Colorado's GIS archives and produced by Colorado Governor's Office of Information Technology[4]. Parcels outside of the service area and not within a 2023 census populated place were excluded. These datasets were spatially merged, and their land uses were aggregated into fifteen common categories (Appendix C). These classes were chosen to condense very similar land uses (such as airfield and airport) but still show distinction between land uses. In addition, functionality was added allowing the filtering of the turf results by Disadvantaged Communities (DAC).

[1] https://denvergov.org/opendata/dataset/city-and-county-of-denver-county-boundary
[2] https://www2.census.gov/geo/tiger/TIGER2023/PLACE/
[3] https://www.arcgis.com/home/item.html?id=e45158155e3e41159aa4090229804672
[4] https://geodata.colorado.gov/datasets/2023-public-parcels-in-colorado/about

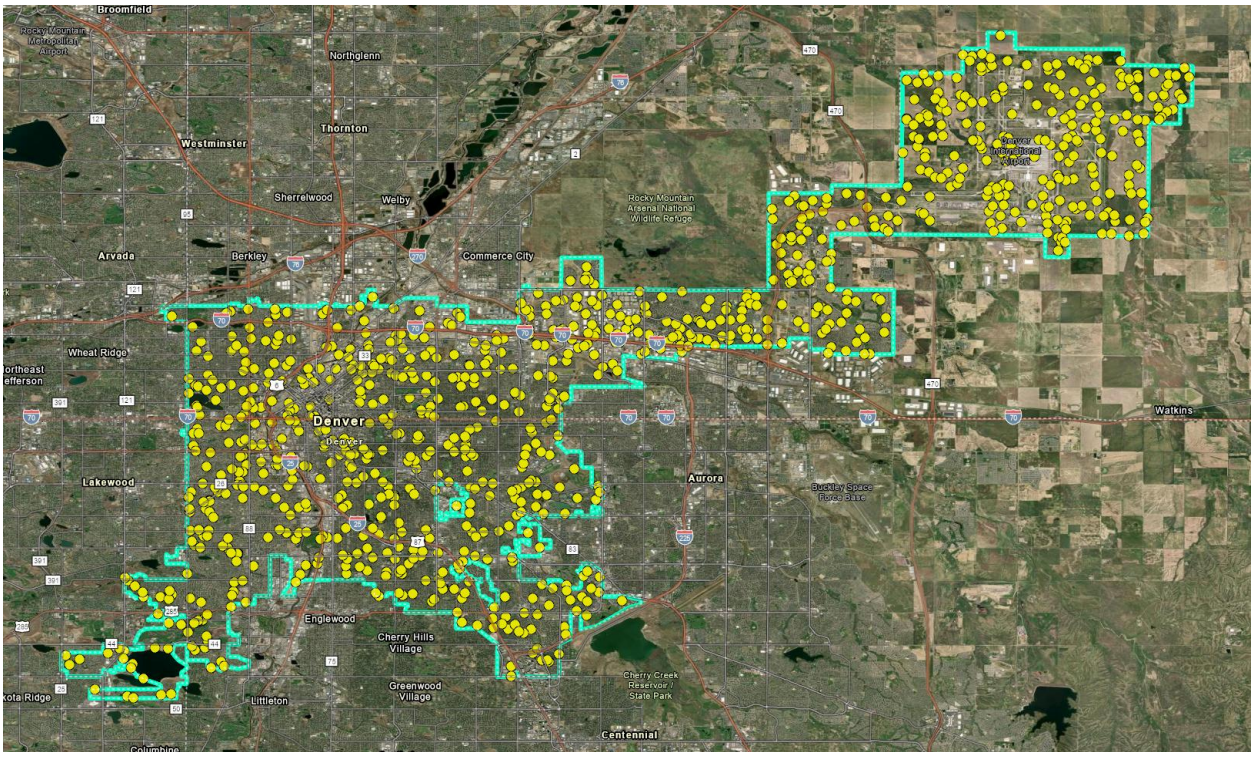

Figure 1. The figure above displays the 1,000 randomly generated points (yellow points) for the validation study distributed across the study area (blue outline).

Because the study area contained 237,623 parcels, contiguous parcels of the same land use, such as a group of neighboring single family home parcels, were merged into one land use group creating 35,092 parcel groups. In addition, parcel groups were again split by DAC, allowing the filtering, for example, all turf area, in all commercial areas, by DAC.
In 213 cases the land cover was not updated to reflect what was visually identifiable in the imagery. These parcel groups were manually recoded as documented in Appendix E.

3.2 Land Cover Processing

Imagery from the U.S. Department of Agriculture's (USDA) National Agricultural Imagery Program (NAIP) 2021 aerial, multispectral imagery[5] was downloaded. This imagery was classified using the California Irrigable Landscape Algorithm (CILA)[6]. This algorithm uses spatial and spectral characteristics of the imagery to accurately output the land cover classes of 'Irrigated Turf', 'Bushes/Trees' and 'Impervious/Other'. Here, 'Irrigated Turf' is specifically defined as 'Photosynthetically Active Vegetation (PSAV) - Turf'. Research provided to the California Department of Water Resources has established CILA to have a high accuracy rate

[5] Grant, Simone, 2018. "National Agriculture Imagery Program: FY2019 Plan Update." GeoPlatform, Federal Geographic Data Committee. Accessed November 20, 2019. https://communities.geoplatform.gov/ngda-imagery/naip-fy2019-plan-update/.
[6] California Data Collaborative 2017 CaDC Statewide Efficiency Explorer Methodology (http://californiadatacollaborative.org/blog/2017/4/28/cadc-statewide-efficiency-explorer-methodology).

when using error—adjusted landscape estimates (Olofsson et al 2013)[7]. A limited amount of imagery was found to have glare on the trees, likely from the aerial imagery being collected late in the day. This resulted in limited areas of trees incorrectly being classified as turf (Figure 2).

Pools were classified using a separate unsupervised classification approach. This methodology identified possible pools as well as a confidence of if that object is actually a pool. For the study area there were 43,810 potential pools. 41,118 of the features were less than 50 sqft and were eliminated. Of the remaining 2,692 potential pool features 2,233 were reviewed for confirmation by a trained analyst manually inspecting the imagery. The result was a total of 1,505 pools that are greater than 50 sqft making up approximately 18 acres.

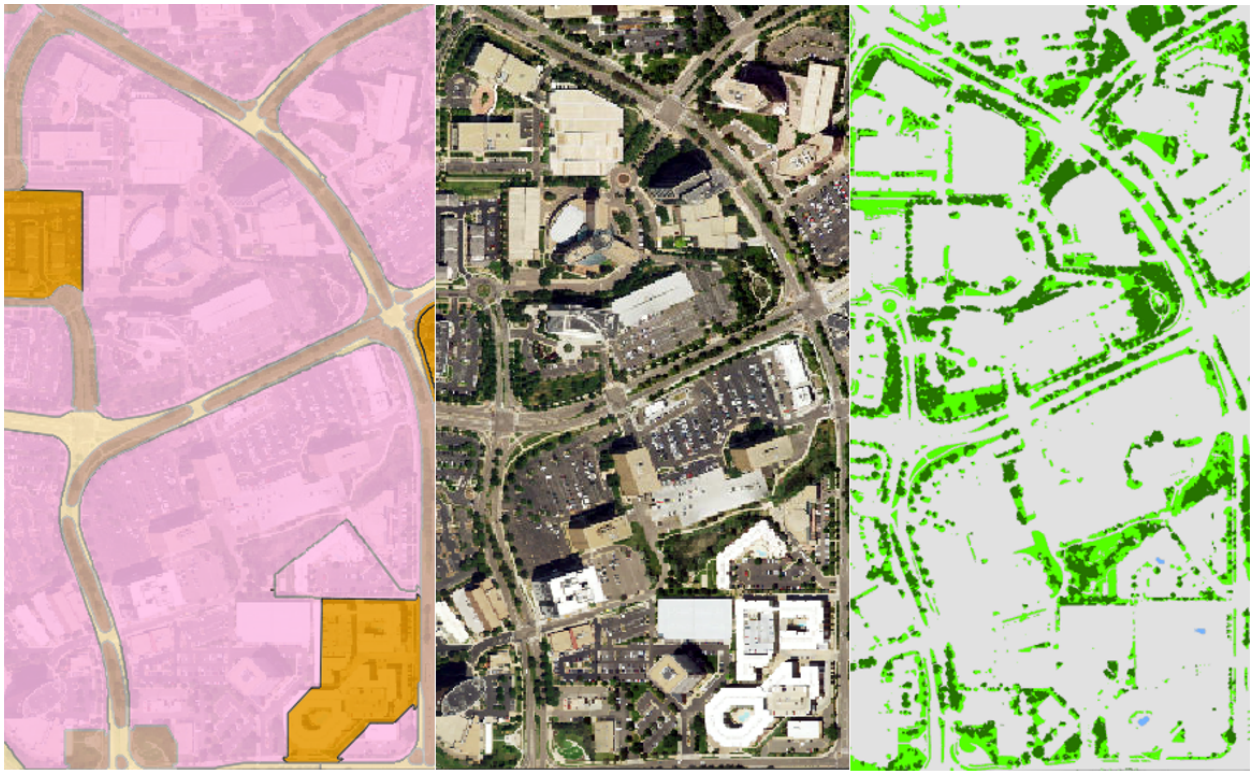

Figure 2. The figure above displays land use parcel groups (left panel), NAIP imagery (middle panel) and the PSAI classified land cover (right panel) with grey as impervious, light green as irrigated turf and dark green as bushes/trees.

[7] Olofsson P, Foody G M, Stehman S V and Woodcock C E 2013. Making better use of accuracy data in land change studies: estimating accuracy and area quantification.

Figure 3. This figure displays an educational parcel group in the NAIP imagery (left panel) and the PSAI classified land cover (right panel). Note that open water is classified as impervious/other (grey) and the pool is correctly classified (blue).

Figure 4. This figure displays a multifamily residential parcel group in the NAIP imagery (left panel), the PSAI classified land cover (middle panel) and the CCD Inferred (right panel).

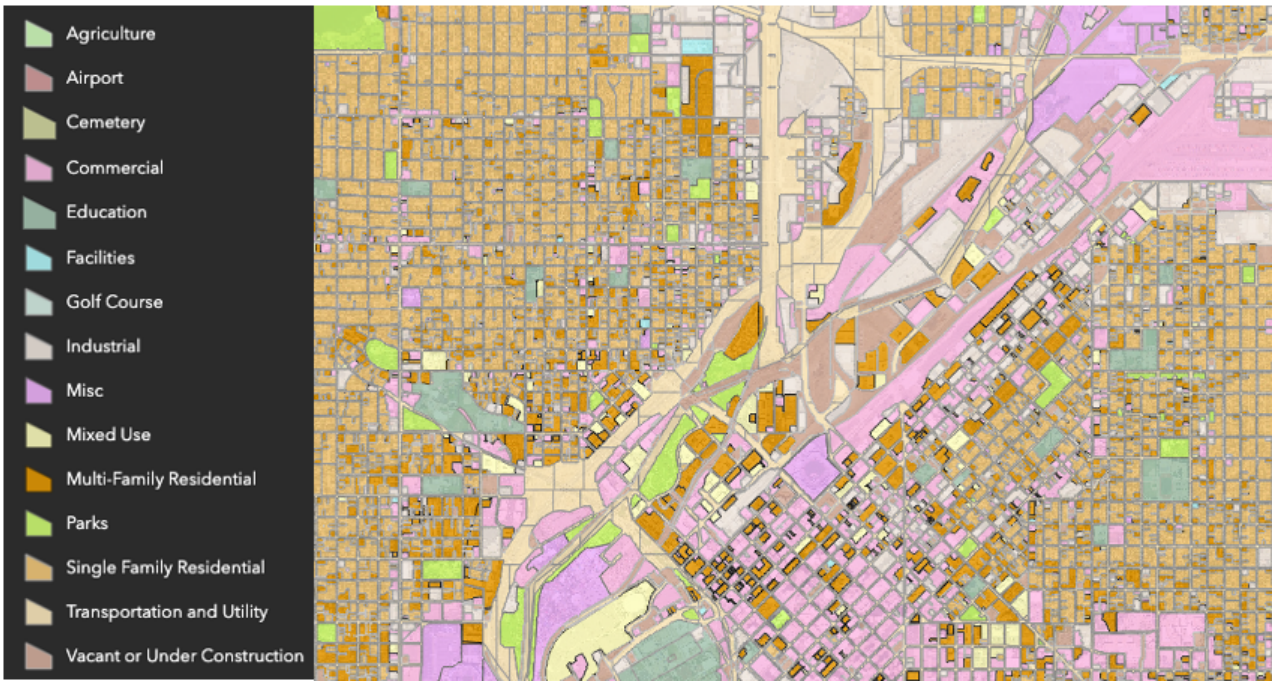

Figure 5. This figure displays the parcel groups in downtown Denver along with the color-coded land use aggregations.

3.3 Assigning Land Cover Values to Parcel Groups

Once classified, the area of each land cover (irrigated turf, bushes/trees, impervious/other and pools) was assigned to each parcel group. This data structure allows the specification of what land uses are 'non-functional', returning the total amount of turf in those areas.

Python scripts in ArcGIS Pro were leveraged to assign the amount of each land cover within each parcel group to that parcel group. A dashboard was constructed to facilitate analyzing turf amounts by land use aggregation (Figure 2).

4. Validation Study

A validation study was executed to compare the identification of irrigated turf in this study with a separate dataset of irrigated turf provided by Denver Water as well as analyze the accuracy of both approaches. The comparison study determined the percentage of irrigated land cover that corresponded between both datasets. Instances where the datasets did not coincide were classified into distinct categories as specified in the report. The manual validation was conducted on a thousand points randomly dropped across the study area (Figure 1).

The PSAI Land Cover Product (LCP) classification demonstrated superior accuracy, aligning with 95% (948 out of 1,000) of the points compared with the manually evaluated dataset. Class 1 (impervious and miscellaneous) achieved an accuracy rate of 99%, whereas Class 2 (bushes/trees + irrigated turf) attained 82% (Appendix A).

In contrast, the CCD Inferred 2021 classification exhibited lower overall accuracy, matching 80% (804 out of 1,000) of the points with the manually evaluated dataset. Class 1 (impermeable and no vegetation) demonstrated a relatively higher accuracy rate of 86%, while Class 2 (high/low vegetation and water) had a lower accuracy rate of 70% (Appendix A).

Subsequently, a similarity assessment was conducted to evaluate the level of agreement between the classifications. Overall, the datasets showed a 93% agreement (Appendix B). Class 2 exhibited the highest level of similarity with 100% agreement, whereas Class 1 showed the lowest similarity at 87%.

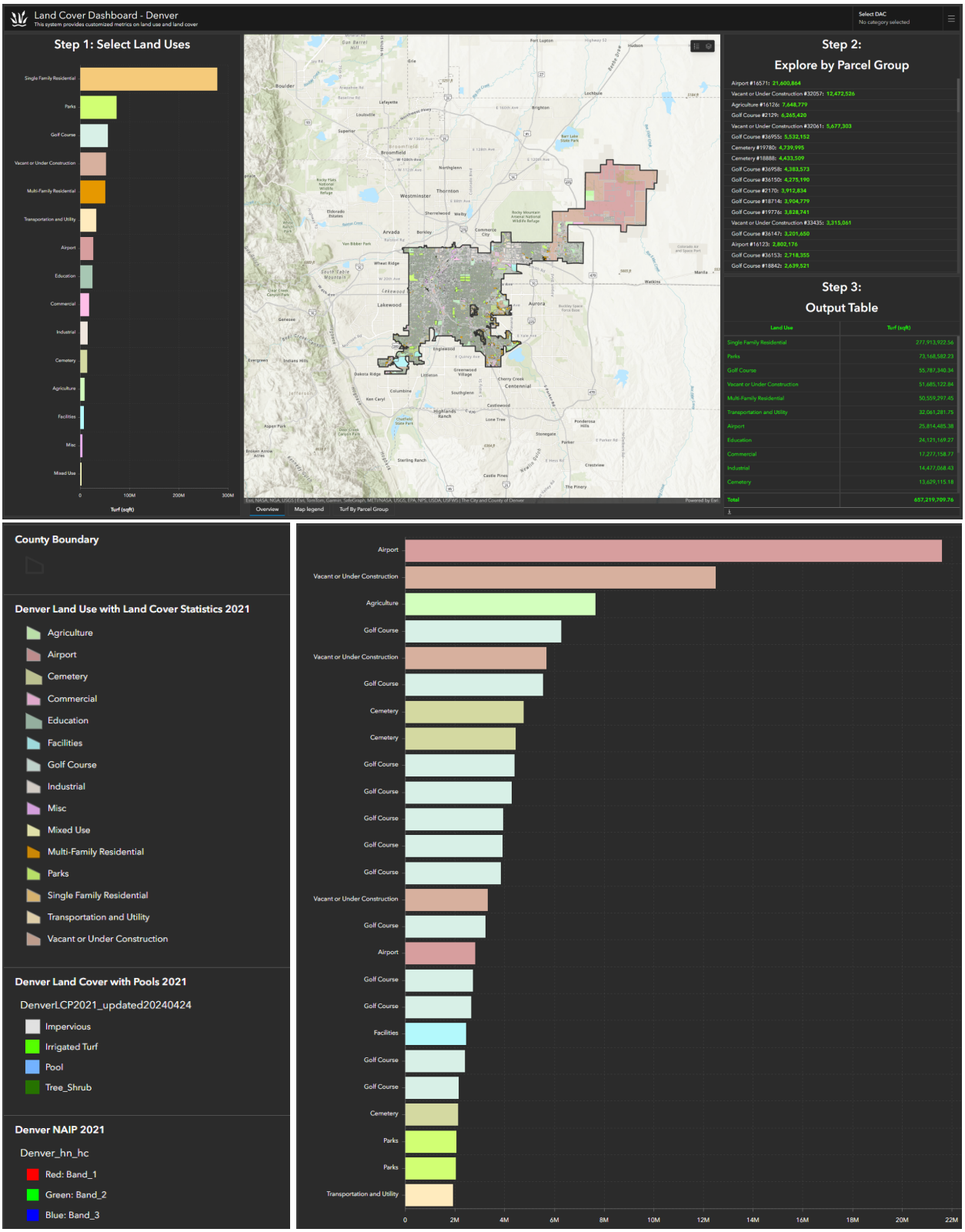

Figure 2. The figure above displays PSAI's Land Cover Dashboard. The top panel shows the main screen with graphs, a map, and two tables. The bottom left panel shows the map's legend, and the bottom right panel shows the map's "Turf By Parcel Group" graph.

5. Results

In Denver County's 155 square mile area, our analysis identified 572 million sqft of turf within developed areas, constituting 13% of the study area. Developed areas exclude airports, agricultural zones, and vacant/open spaces. Within this 13%, approximately 89% is functional turf (including Single Family Residential [SFR], Park, Golf Course, Multi-Family Residential [MFR], Education, Cemetery, Mixed, and Facilities), while 11% is non-functional turf (Transportation and Utility, Commercial and Industrial) (see Appendix B).

6. Discussion and Conclusion

Regarding the comparison between the CCD Inferred product and PSAI's LCP, the primary distinction between these two datasets lies in their methodologies for vegetation classification. CCD categorized all forms of vegetation, ranging from areas devoid of vegetation to those with dense foliage. In contrast, PSAI focused on identifying irrigated vegetation and trees/shrubs, excluding non-irrigated areas like grasslands or intermittently irrigated yards. Appendix D provides a crosswalk illustrating these differing approaches to classification.

These classification variances resulted in minor discrepancies primarily within Class 2 data points across the datasets. The similarity matrix in Appendix B reveals a 13% disparity between PSAI's Class 1 (impervious surfaces) and CCD's Class 2 (vegetated areas). Figure 3 visually emphasizes these differences in vegetation classification between CCD and PSAI. For instance, the depicted area exhibits non-irrigated grass growth. Panel 1 shows no active photosynthesis (dry grass), while the Near-Infrared (NIR) in panel 2 indicates minimal dry vegetation presence. Consequently, PSAI classified this area as Class 1, whereas CCD identified it as low vegetation. Both classifications by PSAI and CCD are technically correct in this scenario, considering their distinct classification methodologies.

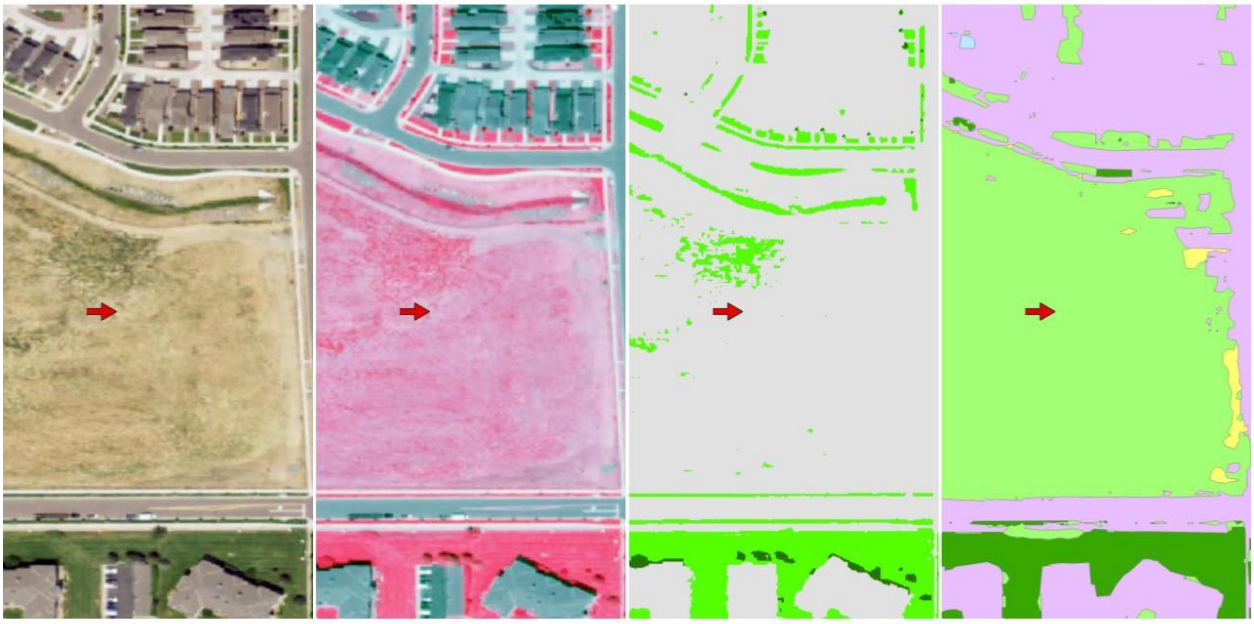

Figure 3. This figure displays four panels of a grassland area with a randomly generated point (red arrow). The first panel on the left displays the 2021 NAIP imagery, the second panel is the same 2021 NAIP imagery but in false color to show the infrared band (Red is Band 4, Green in Band 3, and Blue is Band 2), the third panel shows the PSAI LCP 2021 classification, and the four panel exhibits the CCD Inferred 2021 classification. In this case, both classifications were determined to be correct according to their categories.

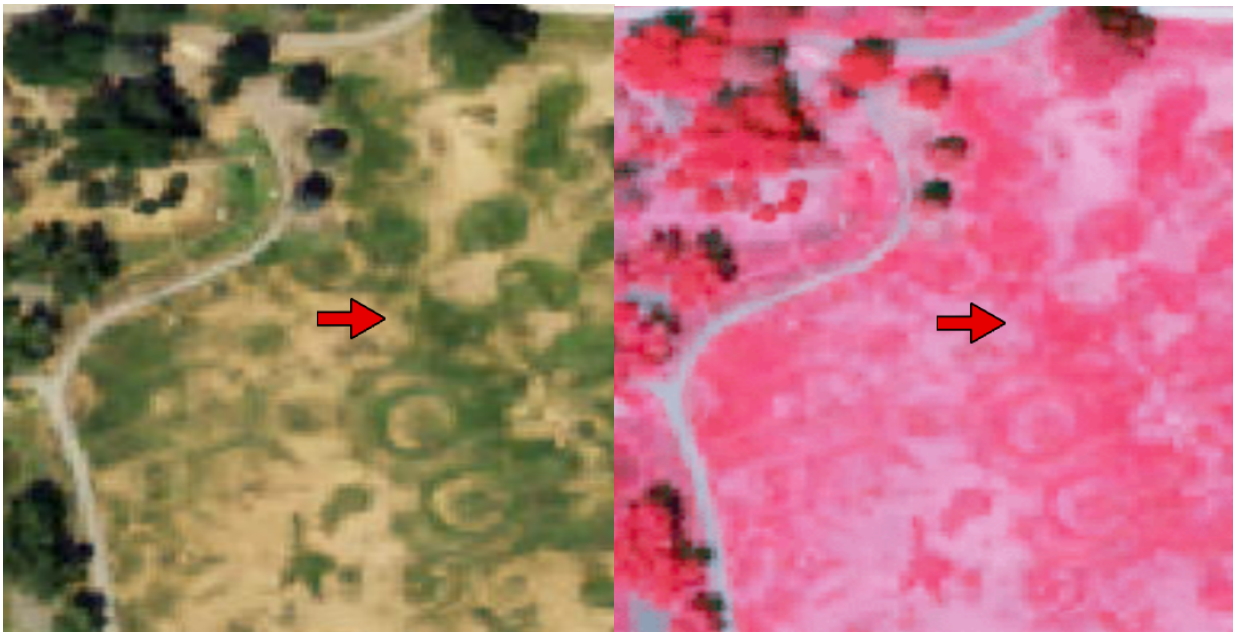

Figure 4. This figure displays two panels, the left is NAIP imagery and the right is NAIP NIR imagery. The point is an example of a historically irrigated park but was identified by PSAI as Class 1 which included non-irrigated turf.

All misclassifications within PSAI's Class 2 (bushes/trees + irrigated turf) category occurred when areas that were actually Impervious (e.g., bare earth) were incorrectly categorized. These errors often arose because analysts detected signs of irrigation in the area, yet the vegetation did not exhibit sufficient vigor or activity to meet PSAI's algorithm threshold for being classified as irrigated turf. Figure 4 provides an example of such misclassification: a park with historical irrigation, evidenced by concentric rings of healthy grass surrounding sprinkler heads. In the NAIP NIR panel, vegetation is visible at the specific point, although less robust than surrounding areas. Consequently, the analyst opted to classify this point as Class 2 (vegetation). This figure underscores the nuanced boundary between irrigated and non-irrigated vegetation.

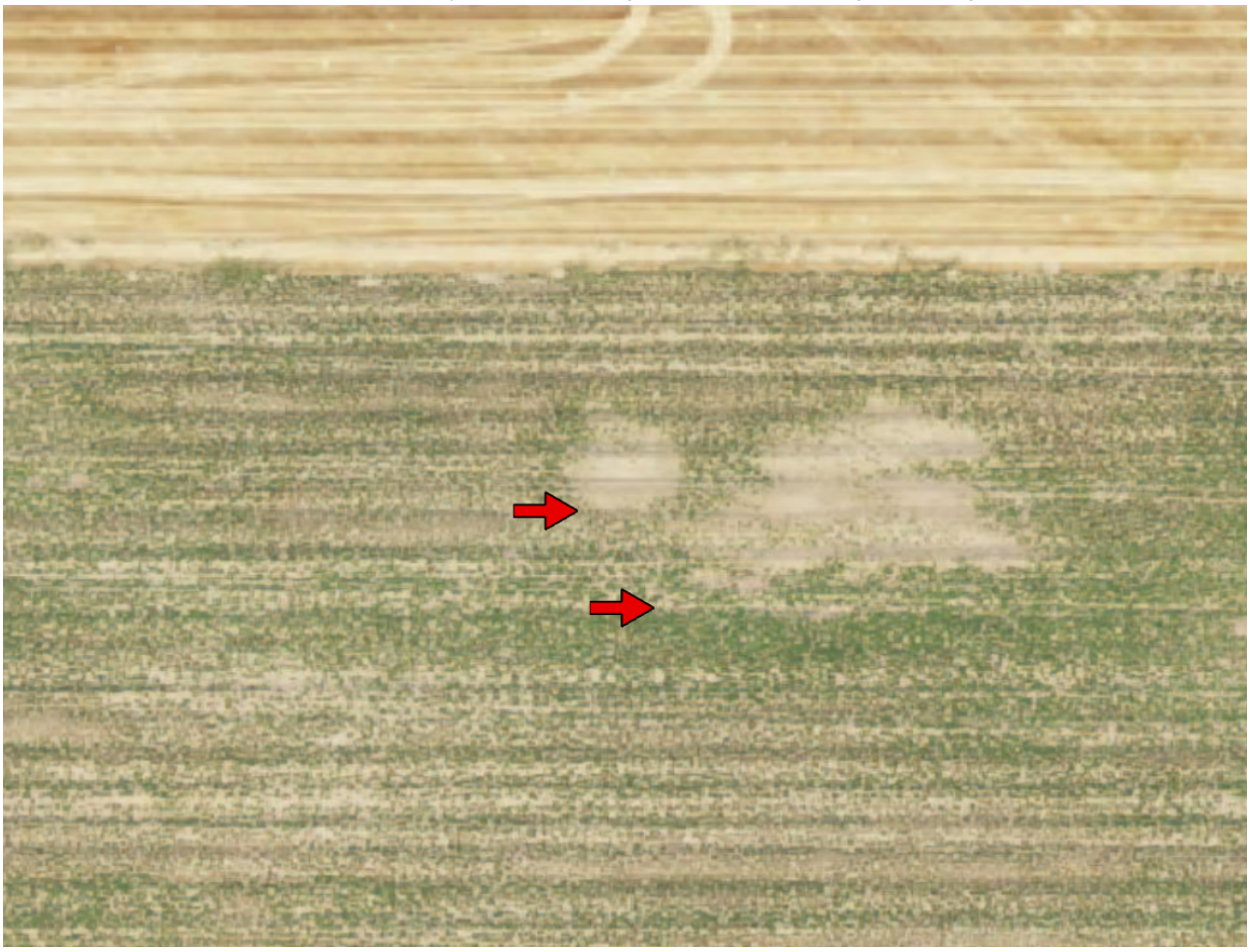

Figure 5. This figure displays an example of points in an agricultural field that were identified by PSAI as Impervious, but the analyst classified these two points as Class 2 (vegetation).

Another contributing factor to misidentification in PSAI's dataset is the spatial resolution of the NAIP imagery, which was 0.6m for this project. PSAI's algorithm largely operates on a pixel-by-pixel basis, relying on individual pixel values for classification. In areas with sparse vegetation, such as irrigated agriculture fields, there are pixels of bare earth scattered throughout. Due to the 0.6m width of these pixels, some areas that appear as bare earth may actually contain irrigated vegetation, as illustrated in Figure 5. This figure depicts a misclassification example in an irrigated agricultural field, where two points were incorrectly assigned to Class 1 by PSAI.

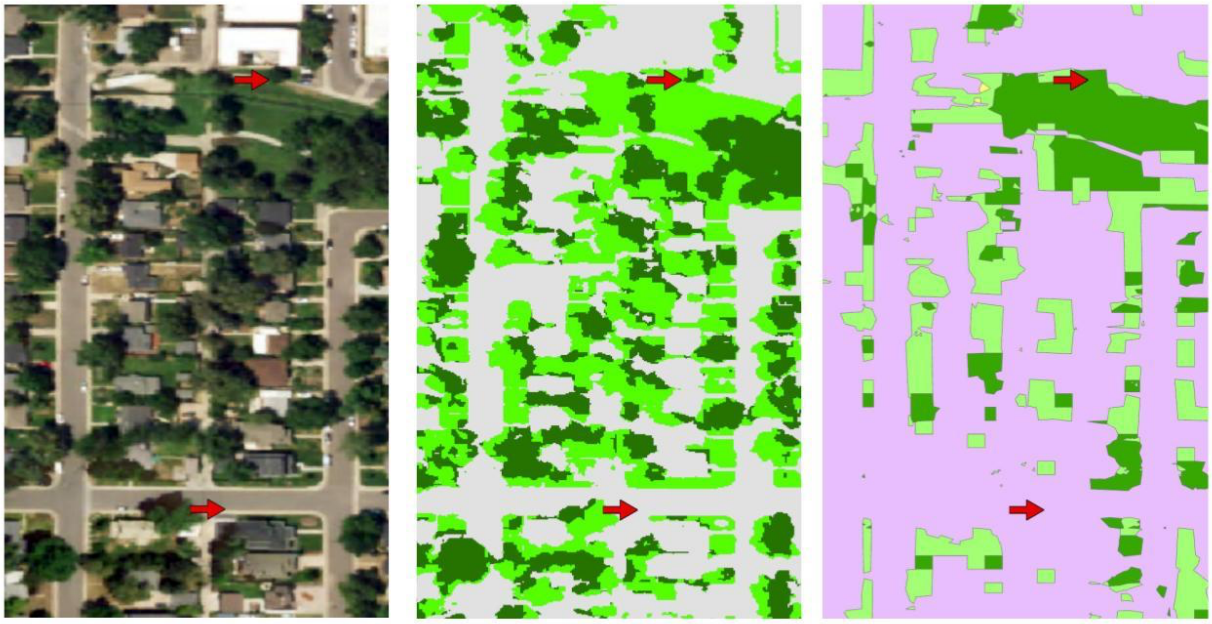

Figure 6. This figure displays three panels of the same locations with two of the randomly generated points for this study (red arrows). The first panel on the left displays the 2021 NAIP imagery, the second panel shows the PSAI LCP 2021 classification, and the third panel exhibits the CCD Inferred 2021 classification. These panels also show the sub-classifications that were not evaluated in light and dark green. The PSAI LCP shows irrigated turf (light green) and trees/bushes (dark green) in the center panel while the CCD panel shows their low vegetation (light green) and high vegetation (dark green on the right panel).

PSAI demonstrated superior accuracy in identifying Class 2 (bushes/trees + irrigated turf) overall. Figure 6 illustrates the accuracy contrast between the datasets. The middle panel, showcasing PSAI's dataset, displays more pronounced vegetation (bright/dark green pixels) compared to the right panel, representing CCD's dataset (similar pixels). Additionally, the representation of impermeable surfaces (gray for PSAI and purple for CCD) is noticeably higher and less accurate in CCD's dataset compared to PSAI's.

Overall, the validation study demonstrates the effective use of NAIP imagery for accurately assessing bushes, trees, and irrigated turf. It also highlights the challenges in comparing datasets that classify classes differently.

Several adjustments could enhance the process to improve results and efficiency. First, optimizing the pool identification process would significantly reduce the time required for manual review of most pools. Second, incorporating non-irrigated vegetation into the land cover classification would broaden the spectrum of identified vegetation types and help reduce misclassifications.

Scaling to all populated places in Colorado would be possible. There are 3,100 square miles of populated places in Colorado[8]. Processing time for this study area, the 153 square miles of the City and County of Denver, took approximately 240 hours, or approximately 1.5 hours per square mile on a local server. With the 3,100 square miles of populated places in all of Colorado, it is expected processing will take 4,650 hours (~194 days). Processing across the state would be possible, but would require parallel processing on cloud-based servers and would likely take several weeks. Note this estimate does not include collecting the data or QA/QC work. Also, land use datasets are not available for all populated areas within the state, which would decrease total processing time. Finally, it is important to note that 2023 NAIP was collected at 30cm per pixel as opposed to the 60cm of the 2021 NAIP used in this study. As such, it is expected that land cover processing times will increase by approximately 25% but will result in better accuracy and results.

This study assessed the extent of irrigated land cover within Denver County, identifying 13,124 total acres of irrigated turf, which represents 13% of the developed area. The study utilized 2021 aerial imagery and an imagery classification algorithm with a 95% accuracy rate. Of the identified turf, 89% is functional (e.g., residential areas, parks, and schools), while 11% is non-functional (e.g., commercial and industrial areas). The findings support initiatives like the Colorado Water Plan by highlighting significant opportunities for turf rebate programs targeting single-family and multi-family residential areas, which collectively account for 7,541 acres of the irrigated turf, as well as provide a way forward for an accurate and affordable assessment of all irrigated turf, by land use, for the State of Colorado.

[8] https://www2.census.gov/geo/tiger/TIGER2023/PLACE/

Appendix A. Confusion Matrix

Confusion Matrix - PSAI

		Actual	
		Class 1	Class 2
Algorithm Results	Class 1	733	46
	Class 2	6	215

Confusion Matrix - CCD

		Actual	
		Class 1	Class 2
Algorithm Results	Class 1	555	108
	Class 2	88	249

Appendix B. Similarity Matrices

Similarity Matrix

	PSAI Class 1	PSAI Class 2
CCD Class 1	643	0
CCD Class 2	96	261

Similarity Matrix - Percentages

	PSAI Class 1	PSAI Class 2
CCD Class 1	87%	0%
CCD Class 2	13%	100%

Appendix C. Assessed Land Cover in Land Use Categories

Land Use Aggregation	Turf (sqft)	Bushes/Trees	Imperv/Misc	Pools
Agriculture	8,084,354	10,746	33,278,892	-
Airport	25,814,485	149,181	528,542,760	-
Cemetery	13,629,115	3,721,153	8,928,418	-
Commercial	17,277,159	7,327,705	231,458,795	34,165
Education	24,121,169	5,333,033	56,374,843	18,670
Facilities	6,556,509	1,491,508	53,906,405	25,539
Golf Course	55,787,340	10,391,059	25,882,874	11,241
Industrial	14,477,068	3,694,266	273,217,493	-
Misc	3,859,724	1,122,234	23,099,547	41,901
Mixed Use	2,224,579	1,397,117	21,143,106	37,019
Multi-Family Residential	50,559,297	35,506,427	245,391,411	316,843
Parks	73,168,582	21,805,132	77,419,489	97,567
Single Family Residential	277,913,923	206,403,176	694,297,138	198,241
Utility	32,061,282	20,696,409	374,742,980	668
Vacant or Under Construction	51,685,123	9,771,743	692,424,210	3,121
Total Turf	657,219,710	328,820,889	3,340,108,358	784,973

Total Dev. (not airport, ag. or vacant)	571,635,748	**% Dev**
Total NFT (Com., Ind., Utility)	63,815,509	11.16%
Total FT (SFR, Park, Golf, MFR, Ed, Cem. Mixed, Fac., Misc)	507,820,239	88.84%

Appendix D. PSAI To CCD Crosswalk

PSAI	< >	CCD
impermeable and misc		impermeable
impermeable and misc		no vegetation
bushes/trees + irrigated turf		low vegetation
bushes/trees + irrigated turf		high vegetation
bushes/trees + irrigated turf		water
pools		N/A

Appendix E. Land Use Recodes

Parcel Group	Existing	Recoded To
6704	Parks	Impervious
2173	Parks	Impervious
6746	Parks	Impervious
13892	Vacant or Under Construction	Transportation
32906	Vacant or Under Construction	Transportation
13743	Vacant or Under Construction	Transportation
12329	Vacant or Under Construction	Park
13498	Vacant or Under Construction	Park
33377	Vacant or Under Construction	MFR
32948	Vacant or Under Construction	Transportation
13479	Vacant or Under Construction	Park
31608	Vacant or Under Construction	Transportation
33120	Vacant or Under Construction	Transportation
30933	Vacant or Under Construction	Transportation
36100	Vacant or Under Construction	Education
33146	Vacant or Under Construction	MFR
33799	Vacant or Under Construction	Park
13441	Vacant or Under Construction	Water
33414	Vacant or Under Construction	Park
33401	Vacant or Under Construction	Park
32563	Vacant or Under Construction	Cemetery
13007	Vacant or Under Construction	Park
35518	Transportation	Vacant or Under Construction
18567	Education	Park
16950	Education	Park
18754	Education	Park
16310	Commercial	Education
163	Commercial	Education

16936	Commercial	Education
1300	Commercial	Park
1582	Industrial	Misc
1520	Industrial	Park
1545	Industrial	Misc
18711	Industrial	Misc
2087	Industrial	Vacant or Under Construction
1599	Industrial	Misc
18398	Industrial	Misc
18702	Industrial	Park
18503	Industrial	Misc
2047	Industrial	Misc
19237	Industrial	Misc
1847	Industrial	Mixed Use
19240	Industrial	Education
19577	Industrial	Education
1490	Industrial	Education
1535	Industrial	Mixed Use
1863	Industrial	Misc
18876	Cemetery	Facility
19843	Cemetery	Commercial
18575	Cemetery	Commercial
1844	Cemetery	Commercial
36087	Cemetery	Commercial
36150	Facility	Golf Course
18141	Facility	Education
18156	Facility	Golf Course
19338	Facility	Misc
1571	Facility	Misc
1630	Facility	Misc
1428	Facility	Golf Course

1455	Facility	Misc
18776	Facility	Misc
1456	Facility	Misc
18136	Facility	Transportation
1423	Facility	Transportation
1459	Facility	Misc
1453	Facility	Misc
18157	Facility	Vacant or Under Construction
19146	Facility	Misc
1410	Facility	Golf Course
18149	Facility	Transportation
18147	Facility	Transportation
36961	Facility	Vacant or Under Construction
18135	Facility	Transportation
36840	Facility	Park
36145	Facility	SFR
18134	Facility	Transportation
18152	Facility	Transportation
36949	Facility	Transportation
16025	Agriculture	Vacant or Under Construction
16045	Agriculture	Vacant or Under Construction
16047	Agriculture	Vacant or Under Construction
16056	Agriculture	Vacant or Under Construction
16030	Agriculture	Vacant or Under Construction
16036	Agriculture	Vacant or Under Construction
16022	Agriculture	Vacant or Under Construction
16028	Agriculture	Vacant or Under Construction
16034	Agriculture	Vacant or Under Construction
16037	Agriculture	Vacant or Under Construction
16038	Agriculture	Vacant or Under Construction
16046	Agriculture	Vacant or Under Construction

16049	Agriculture	Vacant or Under Construction
16039	Agriculture	Vacant or Under Construction
16044	Agriculture	Vacant or Under Construction
16040	Agriculture	Vacant or Under Construction
16031	Agriculture	Vacant or Under Construction
16042	Agriculture	Vacant or Under Construction
35637	Agriculture	Vacant or Under Construction
16026	Agriculture	Vacant or Under Construction
16035	Agriculture	Transportation
16055	Agriculture	Transportation
35633	Agriculture	Vacant or Under Construction
35635	Agriculture	Transportation
35639	Agriculture	Vacant or Under Construction
260	Misc	Education
20266	Misc	Transportation
2274	Misc	SFR
20283	Misc	Transportation
2480	Misc	Transportation
2450	Misc	Vacant or Under Construction
2446	Misc	Vacant or Under Construction
20249	Misc	Vacant or Under Construction
20235	Misc	SFR
2280	Misc	SFR
36333	Misc	SFR
2359	Misc	Park
19885	Misc	SFR
36331	Misc	SFR
2532	Misc	Transportation
20132	Misc	SFR
20238	Misc	SFR
2263	Misc	SFR

20294	Misc	Vacant or Under Construction
2524	Misc	Transportation
20219	Misc	SFR
20243	Misc	SFR
2302	Misc	SFR
2229	Misc	Transportation
2303	Misc	SFR
2455	Misc	SFR
2457	Misc	SFR
2222	Misc	SFR
2469	Misc	SFR
2444	Misc	SFR
2509	Misc	Transportation
2424	Misc	SFR
2438	Misc	SFR
19974	Misc	Park
20285	Misc	Transportation
2508	Misc	SFR
19977	Misc	SFR
2304	Misc	SFR
2486	Misc	Transportation
2520	Misc	SFR
2428	Misc	Transportation
2510	Misc	SFR
20184	Misc	SFR
19892	Misc	SFR
20222	Misc	SFR
2535	Misc	SFR
20240	Misc	Transportation
20037	Misc	SFR
19959	Misc	SFR

2494	Misc	Transportation
20017	Misc	SFR
2398	Misc	SFR
2371	Misc	SFR
2219	Misc	SFR
2262	Misc	SFR
19912	Misc	SFR
2435	Misc	SFR
20023	Misc	SFR
2501	Misc	Transportation
2518	Misc	SFR
19990	Misc	SFR
20228	Misc	Transportation
20063	Misc	SFR
2440	Misc	SFR
2351	Misc	SFR
2423	Misc	SFR
19989	Misc	SFR
2460	Misc	SFR
2241	Misc	SFR
19911	Misc	SFR
2741	Mixed Use	Misc
20316	Mixed Use	Commercial
2753	Mixed Use	Misc
2585	Mixed Use	Education
20371	Mixed Use	Education
20324	Mixed Use	Commercial
20318	Mixed Use	Commercial
2780	Mixed Use	MFR
21574	Mixed Use	Commercial
2549	Mixed Use	Misc

20527	Mixed Use	Misc
20317	Mixed Use	Commercial
20323	Mixed Use	Commercial
2590	Mixed Use	Commercial
2583	Mixed Use	Commercial
20356	Mixed Use	Commercial
20470	Mixed Use	Commercial
20504	Mixed Use	Commercial
2759	Mixed Use	Commercial
20315	Mixed Use	Commercial
20319	Mixed Use	Commercial
2565	Mixed Use	Commercial
20328	Mixed Use	Commercial
20460	Mixed Use	MFR
20320	Mixed Use	Commercial
2584	Mixed Use	MFR
20333	Mixed Use	Commercial
2752	Mixed Use	Commercial
20379	Mixed Use	Misc
20359	Mixed Use	Commercial
2573	Mixed Use	Industrial
2571	Mixed Use	Commercial
20561	Mixed Use	MFR
20365	Mixed Use	Commercial
20530	Mixed Use	Commercial
20434	Mixed Use	Commercial
20542	Mixed Use	Commercial
20329	Mixed Use	Commercial
2692	Mixed Use	MFR
20374	Mixed Use	MFR