TAKING COUNT: A Census of Dinosaur Fossils Recovered From the Hell Creek and Lance Formations (Maastrichtian).

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ABSTRACT:

A census of Hell Creek and Lance Formation dinosaur remains was conducted from April, 2017 through February of 2018. Online databases were reviewed and curators and collections managers interviewed in an effort to determine how much material had been collected over the past 130+ years of exploration. The results of this new census has led to numerous observations regarding the quantity, quality, and locations of the total collection, as well as ancillary data on the faunal diversity and density of Late Cretaceous dinosaur populations. By reviewing the available data, it was also possible to make general observations regarding the current state of certain exploration programs, the nature of collection bias present in those collections and the availability of today's online databases.

A total of 653 distinct, associated and/or articulated remains (skulls and partial skeletons) were located. Ceratopsid skulls and partial skeletons (mostly identified as *Triceratops*) were the most numerous, tallying over 335+ specimens. Hadrosaurids (*Edmontosaurus*) were second with at least 149 associated and/or articulated remains. Tyrannosaurids (*Tyrannosaurus* and *Nanotyrannus*) were third with a total of 71 associated and/or articulated specimens currently known to exist. Basal ornithopods (*Thescelosaurus*) were also well represented by at least 42 known associated and/or articulated remains. The remaining associated and/or articulated specimens, included pachycephalosaurids (18), ankylosaurids (6) nodosaurids (6), ornithomimids (13), oviraptorosaurids (9), dromaeosaurids (1) and troodontids (1).

Over 41,800 isolated bones and teeth, were also located. This number represents only a small fraction of the actual total collection as many of the museums and institutions surveyed were unable to provide complete numbers on isolated elements. Over 46% of these isolated bones and teeth were identified as hadrosauridae, usually identified as *Edmontosaurus*. Isolated elements identified as ceratopsids made up just over 21% of the total. These were generally identified as *Triceratops*. Isolated bones and teeth of tyrannosaurids were significantly less, at only 4.6%. The large difference between the associated and/or articulated remains and the isolated bones and teeth of tyrannosaurids (10.9% down to 4.6%) and ceratopsids (51.3% to 21.5%) is likely due to both a preservational and collection bias towards the larger, more likely to be fossilized, and more likely to be collected, *Tyrannosaurus* and *Triceratops* skeletons and skulls.

Even though small theropods accounted for less than 0.6% of the total recovered associated and/or articulated remains, their teeth and isolated elements were encountered quite frequently. Isolated bones and teeth of dromaeosaurids, troodontids and “unidentified small theropods” accounted for as much as 16% of the total number of isolated remains. This data suggests that there is a tremendous level of collection and preservational bias in the current Hell Creek and Lance sample set Actual small theropod diversity and populations in the Late Cretaceous were most likely much higher than previously considered.

It is highly likely that the fluvial and geochemical environment that dominated the Late Cretaceous of this region was simply too rough and tumble for bones of most genera under the 400 kg live weight

threshold to be preserved. Both preservational bias and collection bias appear to play significant roles in how we currently view the diversity of the Hell Creek and the Lance. This has directly influenced our perception of the end Cretaceous extinction event. It is entirely possible that many genera will never be known from more than fragmentary remains.

INTRODUCTION:

Dr. Dale Russell once remarked that, "I have zero patience for guys who are going to prove that dinosaurs are dying out slowly by counting dinosaur skeletons" (Psihoyos, 1994). I agree with his assessment entirely. What Dr. Russell was essentially saying is that just because dinosaur skeletons are rare or absent in certain zones, does not mean that they were gradually dying off (Russell, 1975). Collection bias or preservation bias may be a significant factor. It might mean that there has not been enough exploration in those zones to find them or that the paleo-environment was outside that animal's preferred natural habitat. It might mean that the geochemical environment was not conducive for its preservation or that the elements are so delicate that they are seldom preserved once eroding out in modern times. Absence of evidence is clearly NOT evidence of absence when it comes to the fossil record (Signor and Lipps, 1982; Foote and Miller, 2007). Counting dinosaurs, in this context, is folly.

Many paleontological studies, such as those involving extinction, ecology, taxonomy or variation often require large datasets (Olszewski, 2007; Steinsaltz and Orzak, 2011; Wang and Marshall, 2016) and well documented stratigraphic evaluation (Wang and Marshall, 2016; e.g. Lyson and Longerich, 2011; Scannela and Fowler, 2014). Basic statistics dictates that certain sample sizes need to be obtained in order to project sufficient confidence intervals (Glover and Mitchell, 2015). The larger the sample, the lower the sampling error. This is one of the reasons why many "big picture" paleobiology researchers (e.g. Raup, 1972; Raup and Sepkoski, 1982; Holland, 2003; Gould and Eldridge, 1977, etc. See also the works of J.J. Sepkowski, A.I. Miller, M. Holland, M. Foote, B. Datillo, D. Jablonski, F.K. McKinney, J. Alroy, etc.) use invertebrate fossils (Russell, 1979), whose datasets and collections are often large, rather than vertebrate fossils, whose collections or datasets are traditionally smaller (Farke, 2014). Absence of large datasets, if n=1, conclusions to many paleontological questions have very little statistical support. Additionally, it is well understood that, increasing the sample size invariably increases the species richness (Raup, 1975; Davis and Pyenson, 2007). Therefore, it's important to understand how much material has been collected, the condition of those collections and where that material is at, prior to evaluating anyone's conclusions regarding dinosaurian remains. In short, before accepting a conclusion as valid, two very important questions must be asked: 1) How much material is actually there to study? and 2) did the study use as much of that available material as possible? In this context, counting dinosaurs is extremely important.

This paper is intended to put a quantitative number on those collections. To determine if there really is enough material to make wholesale judgments on the evolution and extinction, taxonomy and variation of dinosaur taxa in the Hell Creek and Lance Formations, or whether more field work is needed to really solidify various claims. To determine where there is an abundance of data and where the data is too limited for grand proclamations. It is intended to point out the foundation, or lack thereof, from which our current knowledge is based.

<u>Previous studies using census data</u>

One of the earliest censuses of dinosaurs from the Hell Creek Formation, was conducted by White, Fastovsky and Sheehan (1998). They reported the results of a three year study (1987-1990) on the faunal diversity and abundance of dinosaurs in the Hell Creek Formation near Glendive, Montana and Marmarth, North Dakota. Sampling was made from various facies, representing different paleoenvironments in the

Hell Creek ecosystem. Although the team did find "37 articulated fossils", it is not clear whether this means 37 complete articulated skeletons or whether it refers to instances where several individual skeletal elements (arms, legs, portions of tails, skulls, etc.) were found in articulation. (White et al., 1998). The data do not give the relative completeness or even the genus of each skeleton discovered. One of the biggest problems with this study, however, was that much of this material was apparently not collected (Sheehan et al., 1991; Personal communication, Patricia Burke, 2018). It is unclear whether these specimens were eventually collected by other groups or whether they still lie in the badlands. Ultimately, this survey only focused on specimens within their study area and only within that specific time frame. Specimens collected by MPM previously or by other institutions were not used.

Kraig Derstler (1994), provided one of the first major “summaries” of the Lance Formation of Wyoming, and listed many of the known specimens at the time. Based on his counts, *Triceratops* specimens made up 85% of the known [articulated and/or associated] material. *Edmontosaurus* followed at 12% and the remaining dinosaurs were considered uncommon. Derstler's review of the formation, however, included only specimens from the Lance and not the Hell Creek. Obtaining a count of specimens was secondary to a broad description of the known genera.

Russell and Manabe, in 2002, reviewed some of the top museum databases and noted at least 123 articulated skeletons from the Hell Creek. They surveyed several key sites in the upper Hell Creek in an effort to determine the faunal diversity over the last two million years of the Cretaceous. Their intent was to determine the attributes, percentages and regional distribution of the fauna, and to provide a broad picture of the ecosystem. Obtaining a count of specimens available to science was secondary.

Pearson et al. (2002), conducted an extensive survey of specimens from the Marmarth, ND area for the Pioneer Trails Regional Museum (PTRM). This effort collected over 2,200 isolated dinosaur remains and at least 27 partial skulls or skeletons. These specimens were placed in a detailed stratigraphic framework to determine the faunal diversity of the Hell Creek through time especially with regard to the K-Pg boundary. While perhaps the most detailed “census” of their time, the purpose of the research was not about the total number of specimens in collections, but determining whether the extinction event should be considered gradual or catastrophic. The count, like those done in Russel and Manabe (2002), was secondary. Their efforts considered only specimens from this database and none from other institutions.

Neal Larson (2008), provided a comprehensive and detailed review of all known *Tyrannosaurus* skeletons and skulls at the time and did include specimens collected by private groups. This detailed account of 45 known associated and/or articulated specimens provided an excellent census of this one genus, but did not include any other genera from the Hell Creek. It was, perhaps the best review of specimens from a single genera of dinosaur ever written. This study is now over ten years old, however, and many *Tyrannosaurus* specimens have been found since.

Lyson and Longerich (2011), surveyed many of the known major skeletons in an attempt to determine the spatial niche partitioning of Latest Cretaceous dinosaurs. They concentrated on specimens that had clear sedimentological support data to make a link between a genus and its preferred habitat. They developed a thorough and extensive list of some 343 known associated and/or articulated skulls and skeletons, but this list did not consider some specimens that may have been lacking sedimentological data, specimens located in lesser known institutions, isolated elements or elements and skeletons in private collections. Its incredible detail, however, formed a template for this census and most likely any census in the future to follow.

From 1999-2010 an intensive, detailed survey of the Hell Creek Formation of Montana, was run by Jack Horner (Montana State), Nathan Myhrvold (Microsoft and Intellectual Ventures), Bill Clemens (University of California Berkely), Joe Hartman (University of North Dakota) and several others (Horner, 2014). This effort was called the "The Hell Creek Project" and it spent a tremendous amount of time and resources collecting in the Hell Creek Formation near the type section originally described by Barnum Brown in 1907. This extensive exploration program led to the discovery of over 100 new specimens of

Triceratops and another dozen specimens of *Tyrannosaurus*. Their census paper (Horner et al., 2011), as well as Scanella and Fowlers (2014), provided a comprehensive and detailed survey of specimens found in this area, but they listed specimens mostly found during this time period. Their numbers, while impressive, do not represent the entire body of collections or even MOR collections before and obviously, since. The Hell Creek Project does, however, prove that even in areas that have had extensive exploration in the past (Clemens and Hartman, 2014), new fossils are constantly eroding out. It seems that the only reason dinosaur skeletons are still considered "rare", is that we just haven't looked hard enough yet

Various other figures and estimates have been published by the media (Gittleson, 2009), but to my knowledge, no detailed, comprehensive census of the known Hell Creek and Lance material has been attempted since 2011. Part of the problem is that the pace of exploration and collecting has dramatically risen over the last 30 years, leading to large undocumented collections that may or may not be accessible online. Much of this material has not been prepared and many have not been identified, published or officially cataloged. Many of these "new" specimens, rest in private collections, which unfortunately, are often not published and sometimes lack important locality, stratigraphic and historical data.

Institutional Abbreviations:

Please see Appendix 1 and 2 for the names and abbreviations of all 170 known collections used in this census. Detailed notes regarding what was collected, how it was collected, as well as the curator or person in charge who provided this data is included for each collection.

A BRIEF REVIEW OF THE HELL CREEK AND LANCE FORMATIONS

Stratigraphy and Depositional Environments:

The Upper Cretaceous Hell Creek and Lance Formations are some of the most fossil-rich rock units in the United States, if not the world (Figure 1). Every year, both public and private groups travel to Montana, Wyoming, North Dakota and South Dakota in pursuit of these remains and every year they return with new skeletons, isolated elements and teeth. These important fossils have helped change the way we look at dinosaur anatomy, physiology, ecology, evolutionary history and of course, the end Cretaceous-Paleogene extinction event.

The Hell Creek and the Lance Formations are generally considered to be equivalent terrestrial units. That is to say, that they were deposited at approximately the same time during the Maastrichtian Stage, during the last 1.5-1.9 ma of the Cretaceous (Hicks et al., 2002), along the eastern margin of the Rocky Mountains. Despite a few structural and localized faunal differences, they are sedimentologically very similar. They typically consist of alternating, “somber” colored (tan to grey to maroon), fluvially deposited, conglomerates, sandstones, siltstones, shales, mudstones, freshwater limestones, minor coal seams and the occasional volcanic ash bed rich in bentonite (Frye, 1969; Murphy et al., 2002). Paleosols, rich in plant fossils and root traces, are present throughout. Iron concretions and secondary concretionary horizons are very common. Unlike the overlying Paleocene, Tullock or Ludlow members of the Fort Union Formation, which often have laterally continuous beds and thicker coal seems, the Hell Creek and the Lance have rapid lateral facies change due to an abundance of cross cutting of strata and channel fills. This led to highly variable beds, and a more “chaotic” appearance. The Hell Creek Formation tends to be richer in mudstones and carbonaceous shales, whereas the Lance tends to have more fine grained sandstones and siltstones. The Hell Creek is approximately 90-100 meters thick (Murphy, et al., 2002; DePalma, 2010; Horner et al.,

Figure 1: *The Hell Creek Formation.* The Hell Creek and Lance Formations were often referred to as the "Somber Beds" for their somber grey, tan and maroon color tones. Other early workers simply called them the "Ceratops Beds" for the large quantity of ceratopsian material that could be found therein. The above photograph shows a *Triceratops* dig site in the Hell Creek badlands of Meade County, South Dakota, taken in 2017. The bones weathering out in the foreground are the fused nasals and nose horn of a subadult *Triceratops horidus* informally known as "Miss Rene".

2011; Fastovski and Bercovici, 2015), whereas the Lance is further south and west, and considerably thicker. Some estimates suggest that the Lance may be over 1,000 meters thick (Connor, 1992; Finn, 2007).

The Lance Formation was first named and officially described by John Bell Hatcher in 1903 for exposures along Lance Creek, Wyoming. Prior to this time it was simply referred to as the "ceratops beds" (Hatcher, 1903; Clemens and Hartman, 2014). Important expeditions to it, include the Hayden and Meek surveys of of the 1850's and 1870s (Breithaupt, 1999; Jaff, 2000); the Hatcher expeditions of 1890-1893 for O.C. Marsh (Hatcher, 1907), The University of Kansas/Barnum Brown expeditions of the late 1890's (Kohl, et al., 2004), The Sternberg expeditions of the early 1900's (Lippincott, 2015), The University of Wyoming expeditions of the 1950's -1960's, The University of California Berkeley expeditions of the 1950's to 1970's (Clemens and Hartman, 2014), as well as dozens of both public and private teams which have come out every year since.

The Hell Creek Formation was formally described by Barnum Brown, in 1907, for exposures along "Hell Creek", north of Jordan, MT; the site has since then been flooded by Fort Peck Reservoir (personal communication Ken Carpenter, 2018). Early expeditions include those made in the 1850's by Hayden and Meek, and of course, those made by Brown himself between 1900 and 1910. Additional major expeditions included: The Science Museum of Minnesota trips of the early 1960's, the LA County Museum of Natural

History expeditions of the mid 1960's to 1970's (led by Harley Garbani), the UCMP expeditions of the 1970's-early 2000's (Clemens and Hartman, 2014), the Museum of the Rockies, Hell Creek Dinosaur Project from 1999-2010 (Horner et al., 2011; 2014) the Marmarth Research Foundation expeditions of the late 1990's and early 2000's, and the University of Kansas expeditions in the early 2010's through the present (personal communication David Burnham, 2017). Work on the South Dakota side of the line continued with explorations by the South Dakota School of Mines and Technology throughout the 1980's and 1990's, the Black Hills Institute expeditions of the 1980's to the present, the West Palm Beach/University of Kansas digs in the early 2000's and the Triebold Paleontology expeditions of the mid 1990's to present. At present, there are at least 60 different museums, science centers, universities, commercial collectors, ranchers and private collectors which dig and explore these units annually.

These formations represent an ancient coastal floodplain environment, filled with swamps, marshes, lowland forests, estuaries, broad, but shallow, meandering river systems and occasional ox-bow lakes (Fastovski, 1987; Derstler 1994; Pearson et al., 2002; Fastovski and Bercovici, 2015). As the Rocky Mountains slowly rose to the west, the Hell Creek and Lance Formation expanded eastward, filling in the great basin that was the Western Interior Seaway (Murphy etal., 2002). Along this irregular, swampy coastline, dinosaurs flourished.

Other time equivalent formations include the Frenchman and Scollard Formations of Canada, the Laramie and Ferris Formations of southern Wyoming, the Denver and Laramie Formations of Colorado and the McRae Formation of New Mexico. Together, this entire group of rock formations outcrop sporadically over 1,200 miles along the Front Range of the Rockies and along the outer rims of the inter-montane basins of the western United States and Canada. For the purpose of this study, only dinosaurs from the Hell Creek Formation of Montana, South Dakota and North Dakota; and the Lance Formation of Wyoming are considered. Fossils contained in these beds represent some of the last dinosaurs to exist on the planet prior to the great K-Pg mass extinction.

Dinosaurs of the Hell Creek and Lance Formations:

To date, over 28 named genera of dinosaurs have been reported in these formations, with new specimens discovered each year. The ceratopsids are represented by at least three genera; *Triceratops* Marsh, 1889, *Torosaurus* Marsh, 1891 and *Leptoceratops* Brown, 1914 (Ostrom, 1978). An additional three others; Nedoceratops Marsh, 1889 (Ukrainsky, 2007; Farke, 2011), *Tatankaceratops* Ott and Larson, 2010 and an unnamed ceratopsid (personal communication, John Carter, 2015; Bob Dietrich, 2017) may also exist, though the latter has yet to be formally described. Hadrosaurids are represented by *Edmontosaurus* Lambe, 1917 and possibly by the rare *Anatotitan* Chapman and Brett-Surman, 1990, (Glut, 1997) though this latter genus might just represent an older ontogenic stage of *Edmontosaurus* (Horner et al., 2004; Campione et al., 2011). There has also been some evidence for a lambeosaurine hadrosaurid in the Hell Creek (Boyd and Ott, 2002), but if present, appears to have been very rare. *Thescelosaurus* Gilmore, 1913 (Gilmore, 1915; Boyd et al., 2009) is the primary small, basal ornithopod, but there has been some isolated evidence to suggest the possibility of another, undescribed basal ornithopod (Personal communication, Mike Triebold, 2005). Pachycephalosaurids are represented by up to four genera. These include *Pachycephalosaurus* Brown and Schlaikjer, 1943, *Stygimoloch* Galton and Sues, 1983, *Dracorex* (Baker et al., 2006) and *Sphaerotholus* Williamson and Carr, 2003. Some, however, (Horner and Goodwin, 2009) have suggested that only one of these, *Pachycephalosaurus,* is valid. The armor plated dinosaurs are represented by at least two genera; *Ankylosaurus* Brown, 1908 (Carpenter, 2004) (an ankylosaurid) and *Denversaurus,* (Bakker, 1988) (a nodosaurid) though this material is surprisingly rare (Carpenter and Breithaupt, 1986). Tyrannosaurids are represented by the super predator, *Tyrannosaurus* Osborn, 1905 and the controversial, *Nanotyrannus* Bakker et al., 1988, which others have suggested is a juvenile morph of *Tyrannosaurus* (Carr, 1999). Ornithomimids are represented by one or possibly two genera including

Ornithomimus Marsh, 1890, and/or *Struthiomimus* Osborn, 1916 (Marsh, 1892; Russell, 1972; Longerich, 2008) though Ornithomimid classification is currently unresolved. At present, most authors and curators appear to identify the Hell Creek/Lance specimens as *Struthiomimus sp.* or *Struthiomimus sedens* (see Longerich, 2008) though *Ornithomimus* may be more accurate (Personal communication, Kenneth Carpenter, 2019). Oviraptorosaurs may include up to three separate genera. These include the recently described *Anzu* (Lammana et al., 2014), the enigmatic *Leptorhyncos* (Longrich et al., 2013) and two smaller, undescribed specimens with BHIGR (Personal communication, Peter Larson, 2015; 2017). Dromaeosaurids are represented by at least two and possibly up to five genera. These include the recently named *Acheroraptor* Evans et al., 2013 and *Dakotaraptor* DePalma et al., 2015 as well as cf. *Saurornitholestes* Sues, 1978 (Larson and Currie, 2011), *Richardoestesia* Currie et al., 1990 and another undescribed genus known only from teeth (Stein, in preparation). Troodontids include two genera known only from teeth and very rare, isolated elements. These include: cf. *Troodon* Leidy, 1856 (Larson and Currie, 2011) and *Pectinodon* Carpenter, 1982 (Larson and Currie, 2013) though the latter may represent a second tooth morphology in cf. Troodon (personal communication, Kenneth Carpenter, 2018). Additional enigmatic small theropods known from either fragmentary material or teeth include: an undescribed alvarezsaurid, *cf. Albertonychus* (?)(Longerich and Currie, 2009), *Zapsalis* and *Paronychodon* (Larson and Currie, 2013) the latter of which may or may not be a dinosaur (Personal communication, Frank Francino, 2017).

Of all these genera, only eight are known from more than one, reasonably complete (>50%), skeleton. These include: *Triceratops*, *Edmontosaurus*, *Thescelosaurus*, *Ankylosaurus*, *Denversaurus*, *Tyrannosaurus*, *Struthiomimus sp.*, and *Anzu*. Several others are generally accepted, though the material is limited. These include *Pachycephalosaurus*, *Dakotaraptor* and *Acheroraptor.* The rest are known from very fragmentary remains, teeth or are disputed (e.g. *Torosaurus* or *Anatotitan*), for one reason or another. Many of these are likely valid taxon, but the amount of material for study is too limited for much detail.

METHODOLOGY:

Research on this new census began during the spring of 2017 and concluded by February of 2018. A comprehensive list of institutions known to have Hell Creek and Lance dinosaur material was compiled based upon common knowledge, available literature, news reports, website data, social media posts, blogs, visitor photos, etc. Social media, and word of mouth, proved particularly useful as several more obscure collections were located. Many private collectors also came forward as a result of inquiries to sites such as *Facebook*, the *MyFossil Project* and *The Fossil Forum*. A total of over 170 museums, universities, public and private institutions, companies, researchers and collectors, were found to hold collections of Hell Creek and Lance material.

This list was further subdivided into several categories based upon the collections ownership, the groups stated goals and the perceived and stated "stability" of the collection (See Appendix 1 and 2). Stability in this case, is defined as, the degree to which those collections are considered permanent. "Highly Stable" collections include larger, older, well-established public or private museums and universities who are charged with caring for specimens "in perpetuity" for the benefit of science. Many, if not all of these institutions, hold BLM permits for collecting and thus, legal restrictions that prevent them from selling or trading specimens from or into their collection. A second category included what I call, "Reasonably Stable" collections. These included certain private museums, science centers, private educational companies, private collectors, and organizations that could legally sell and/or trade specimens, but who often have collections or portions of their collection that are not expected to be sold to other private entities in the near future. Often these had important fossils that would, most likely, through sale, trade or donation, wind up in more stable collections one day. These groups do not have any legal limitations on what they may do with this material, but simply a motivation to maintain the collection in its current state for as long as possible. “Transitionary” or unstable collections include those owned by some private commercial companies or individuals whose exclusive goal is to sell or trade the material to someone else. These collections may be well known, but they are expected to trade hands in the short term with no limitations. This means that their locations may change unexpectedly and may one day wind up in a collection that is not accessible. For this last category, only major skeletons, most likely to wind up in a permanent or semi-permanent collection were counted. Isolated bones and teeth owned by transitionary, commercial groups were often quite numerous and traded too frequently to track. These were not inventoried.

Ownership categories included: 1) Public Museums, Institutions and Universities, 2) Foreign Museums and Universities, 3) Regional and Local Museums (city or county owned museums located nearby Hell Creek/Lance outcrops) or Non-profit Groups, 4) Private Museums, Science Centers, Large Commercial Companies and Educational Companies, 5) Large Private Collections, and 6) Exclusively Commercial Collections. The first three groups of institutions are considered largely permanent, “public” repositories and their collections regarded as “stable”. The second two categories are considered “relatively stable collections” and the last is considered “transitionary”, i.e. specimens are often sold or traded frequently. Counts are subtotaled at the end of each category allowing the reader to determine for themselves the validity, reliability and repeatability of each dataset

Each institutions website, if available, was then reviewed to see if the museum or institution had an accessible online database (please see Appendix 2 for all url's used). If so, census numbers were obtained directly from the database unless additional information or follow up questions were required. If the institution did not have a publicly available database or there were questions generated from that review, an email letter of inquiry was sent to the collections manager or curator in charge of the collection. If there was a positive response, curators were asked to send data in spreadsheet form, from internal databases or fill out a census form based upon their internal records. If there were no internal spreadsheets or offline databases to obtain a count, collections managers and curators were asked to estimate the number of specimens in their collections to obtain a “ball park” or rough estimate.

If there was a negative response or no response from the initial email inquiries, an attempt was made to call the curator/collections manager in charge directly. If there was still no response, a partial census of the collection was made through available scientific literature, web site descriptions, blog posts, social media or visitor photographs. As a result of these issues, all data herein should be considered a *minimum* number of specimens and not the actual number of available specimens. In many cases the actual number of specimens is most likely much, much higher. Each and every year, these numbers will increase.

Attempts to record Hell Creek and Lance Formation collections in foreign museums and universities were also made, but most of these did not have online databases and language barriers prevented much detail. Several efforts were made to post emails to curators or to general museum mail boxes, but these were seldom forwarded to the appropriate staff and few replied. In this case, available literature or referenced specimens were the primary source of information. This was supplemented with website descriptions, newspaper articles, and visitor photos posted online. In some cases, Google Maps allowed for a partial or complete walkthrough of the exhibit halls, enabling me to zoom in on exhibits and displays. Colleagues more familiar with that particular collection were then asked to confirm or deny the presence of original material in these foreign exhibit halls. The online database of commercially collected specimens, many of which were sold overseas, by Winters (2014), was a huge asset in this regard.

When reviewing online databases or spreadsheets, census data was taken based upon five broad categories. These included: good skeletons (>50%), partial skeletons (<50% complete), isolated skulls, isolated elements and isolated teeth. Composite skeletons were broken down into their component parts when possible. When exact percentages were not available an estimate was made based on photographs or email inquiry. Only original, non-cast, dinosaur material was counted. Other organisms like turtles, crocodilians, mammals, fish etc. were also not counted and beyond the scope of this project. These specimens often outnumbered the dinosaur collections 3-1.

Since the taxonomic identification scheme varied from one institution to another, counts were often made on the generic or family level only. In many cases, specimens could only be confirmed to family level. Usually, the identification that was made in the database record was the one used in the count. In rare circumstances, where firsthand knowledge of the specimen was possible or good photographs were available the identification was changed or updated to a more modern one. This was particularly applicable in older collections that often used outdated classification schemes (e.g. *Trachodon* vs. *Edmontosaurus*) or when photographs clearly showed an incorrect identification. When there was any ambiguity the identification recorded in the database was the one used.

To simplify the process across multiple institutions, counts were made in the following 14 broad taxonomic categories: 1) Ceratopsids (including specimens recorded as: *Triceratops*, *Torosaurus*, *Nedoceratops*, *Tatankaceratops*, *Leptoceratops* or unidentified Ceratopsidae), 2) Hadrosaurids (including specimens recorded as: *Edmontosaurus*, *Anatosaurus, Anatotitan*, *Trachodon* or other Hadrosauridae), 3) Thescelosaurids (including specimens recorded as: *Thescelosaurus*, Thescelosauridae or basal ornithopoda), 4) Pachycephalosaurids (including specimens recorded as: *Pachycephalosaurus*, *Stygimoloch*, *Dracorex*, *Sphaerotholus*, *Stegoceras* or other Pachycephalosauridae), 5) Ankylosaurids (including specimens recorded as: *Ankylosaurus* or Ankylosauridae), 6) Nodosaurids (including specimens recorded as: *Denversaurus*, *Edmontonia* or Nodosauridae), 7) Unidentified ornithischians or Ornithopoda, (from photos these were usually a mix of hadrosaurid and ceratopsid bones and/or teeth), 8) Tyrannosaurids (including specimens recorded as: *Tyrannosaurus*, *Nanotyrannus*, *Aublysodon* or other Tyrannosauridae), 9) Ornithomimids (including specimens recorded as: *Struthiomimus*, *Ornithomimus* or Ornithomimidae), 10) Oviraptorosaurids (including specimens recorded as: *Anzu, Leptoryhnchos, Caenagnathus, Chirostenotes, Caenagnathidae* or Oviraptorosauridae), 11) Large Dromaeosaurids (including specimens recorded as: *Acheroraptor*, *Dakotaraptor*, *Dromaeosaurus,* or other large-bodied (>60kg) Dromaeosauridae), 12) Small Dromaeosaurids (including specimens recorded as: *Saurornitholestes, Richardoestesia gilmorei*, and/or other small-bodied (<60kg) dromaeosauridae), 13) Troodontids (including specimens recorded as: c.f. *Troodon*, *Pectinodon* or other Troodontidae), and 14) Unidentified Theropods (which often was a catch-all, and included several collections of unidentified dromaeosaurid teeth, bones, unidentified theropod odds and ends, and anything related to *Paronychodon*, *Zapsalis*, *Richardoestesia isosceles*, *Avisaurus*, and the undescribed alvarezsauridae *cf. Albertonychus)*. For convenience and aesthetics, all clearly identified large and small dromaeosaurids and troodontids were combined into one column for the appendix and data tables. Ankylosaurids and nodosaurids were also combined for similar reasons.

Addressing the validity of controversial taxa was beyond the scope of this paper and no inference based on the above groupings should be made one way or the other. Since all of the controversial taxa were included in the same category as the uncontroversial taxa, this effectively negates any bias in the family level portion of the census.

Some databases lumped large collections of teeth or bones under a single catalog number with no description beyond this. Others recorded these multiple specimen sets under a single catalog number, but remarked that it included “x” number of teeth or “x” number of elements. In the former case, since there was no data on the actual quantity of teeth in that set, the set was counted as 1+. In the latter, where description was detailed enough to make an accurate count, the set was counted to the description. This means that certain institutions will have significantly larger collections of individual bones and teeth than catalog numbers.

In some cases, a single catalog number or site contained multiple bones, without any clarification regarding their association. In this circumstance, in the absence of any other literature, personal knowledge or personal communication, referral was based on the available description or photos of the specimens. Some of these were considered fragmentary skeletons and others were counted as isolated elements. When in doubt, these were considered isolated elements not in association.

In other cases, a single catalog number referred to a specimen as "associated", but the available listed or photographed material consisted of less than 1 % of an average dinosaur skull or skeleton (three or less elements- considering 300+ bones in the average dinosaur skeleton). For the purposes of this paper, associated skeletons and skulls had to have at least three bones or more, some form of articulation, or some evidence to connect them, to be considered fragmentary/partial skulls or fragmentary/partial skeletons. Where there was uncertainty, these were considered isolated elements not in association. There were several cases where a curator, collections manager, or researcher referred to a partial skeleton, but upon closer inspection the specimen consisted of less than 3 bones and no articulation. This was particularly true with estimated collections based primarily on available literature such as, Pearson (2002) and Scanella and Fowler (2014). When there was doubt, the material was counted as isolated elements and not elements in association.

Only specimens that had been collected and prepared and curated were included in this census. There were numerous cases where skeletons and skulls were referenced as being surveyed or discovered, but were not collected (Sheehan et al., 1991; Pearson, 2002; Scanella and Fowler, 2014; Horner, 2010). In most cases, these reported, but uncollected specimens were not counted. There were also multiple instances where a curator or collection manager alluded to a large collection of isolated remains in storage (e. g. NDGS, DDM, MOR, Fort Peck Interpretive Center), but these fossils had not yet been prepared or formally accessioned. These may have been included in the rough estimates, but not in the detailed counts. This means that the total rough estimate of isolated bones and teeth is significantly higher than the detailed family counts.

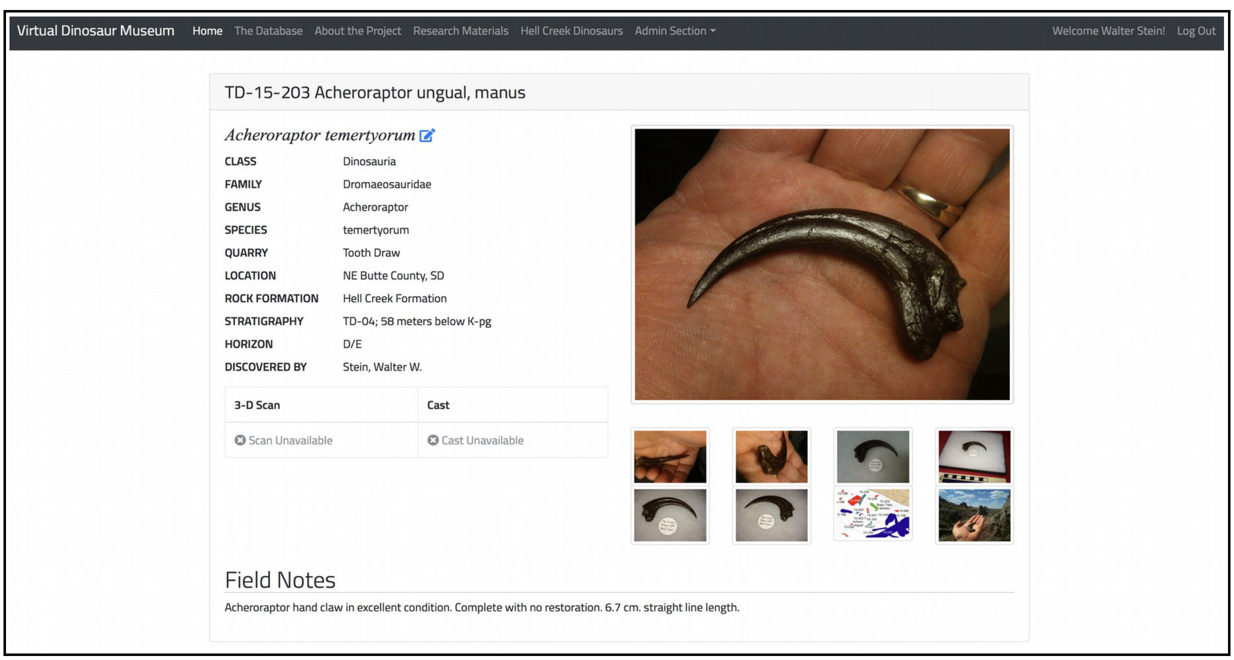

Figure 2: *New Hell Creek Database.* Another component of the project, was the development of our own online database for our research grade dinosaur collection. The PaleoAdventures Research Collection Database (PARC) at www.virtualdinosaurmuseum.com took approximately 4 months time to develop (part-time) and populate (over 700 specimens and counting) on a budget of less than $2,000. Every institution with significant collections of fossils should be in the process of creating their own online database for researchers.

On rare occasions, a curator or collections manager would allude to a skeleton or skull that had been discovered in the field, but only portions of which had been recovered and prepared. In this case, the specimen was most likely counted, if the number of currently recovered elements exceeded the 1% restriction for "percent complete", and the curator or collections manager indicated that they intended to recover the rest within the next year or so.

The data were then compiled into various tables and graphs using Apache Open Office. Genera were ranked due to estimated adult body mass (modified from Paul, 2010; Paul 2011; Brown et al., 2012; Gorman and Hone, 2012; Campione et al., 2014) and counts in each genera analyzed using the application "Taxon" version 1.0.1. The data was then plotted on simple graphs and rarefaction curves. Chao-1 numbers and other data where generated by the program and estimates of evenness of the sample, bias, suspected taxonomic diversity of the units inferred. Statistical analysis of the dataset should be considered preliminary and additional tests and metrics will be applied in future papers.

The complete results of this census can be found in Appendix 1 of this paper as well as on the website www.virtualdinosaurmuseum.com under the "research" tab (Figure 2). I will continue to maintain and update the database periodically, so any errors in counting can be corrected. If errors are discovered, please contact me directly at stein151@comcast.net. In future updates I hope to provide a complete list of all 653+ specimens sorted by institution and catalog/accession/field number.

THE RESULTS:

I. A Review of Online Databases and Their Availability:

Of the 170 groups known to possess Hell Creek and Lance dinosaur remains, only 65 (or roughly 38%) were able to relay detailed or complete census numbers (Table 1). Of these, less than half (30 groups or 17.6%) had a fully accessible, online database from which to obtain a count (Table 2). Another 32 groups/collectors were able to at least provide rough estimates of their overall collections or a partial census with major skeletons and skulls being the most accurate.

Many of these groups appeared to be generally supportive of the project and if the data was not readily available, several curators and collections managers made significant efforts to acquire it and pass it forward. Some, like TGM, UWGM, and VMNH, even took up new internal inventory projects of their own. Others, like BHIGR, TCMI, or RAM pulled their counts directly from internal databases or personal knowledge of the collection. Some, like FMNH and DMNS, sent spreadsheets of the collection, from internal databases, enabling me to run a very detailed count of their fossils. In total, 97 out of 170 museums, universities and collectors (57%) provided very accurate numbers for skeletons and reasonably accurate numbers for isolated bones and teeth.

Of the remaining 73 groups/collectors, 30 were either unable to be reached or were not directly contacted, 31 did not reply despite multiple email and phone requests, and 12 did reply but could not provide any reliable information. Of those who did reply, response to the census was mixed. Some curators/collections managers/private collectors expressed a willingness to help, but they simply did not have the information readily available to them. Some did not feel confident in estimating or were overwhelmed with other collection issues. A handful of others, such as SDSMT, were not interested in participating at all in the census. It can only be assumed that the 31 groups who did not return multiple emails and phone calls simply did not wish to participate. Unfortunately, this applied to 10 of the 55 known public collections in the USA.

Of the groups whose contact information was unavailable, all were primarily from foreign

Availability and Response to the Census

	Public Museums and Universities	Foreign Museums	Regional and Local Museums	Private Museums and Educational Companies	Private Collections	Commercial Collections (skeletons only)	Combined Totals for All Groups
Provided a Complete or Detailed Census by database or personal communication	50.1% (28/55)	31.4% (11/35)	23% (3/13)	36.8% (7/19)	57.7% (15/26)	4.5% (1/22)	38.2% (65/170)
Provided a Partial Census or Rough Estimate via personal communication	23.6% (13/55)	8.6% (3/35)	38.5% (5/13)	26.3% (5/19)	7.7% (2/26)	18.2% (4/22)	18.8% (32/170)
Did respond, but could not provide or chose not to provide any pertinent data	7.3% (4/55)	0% (0/35)	7.7% (1/13)	5.3% (1/19)	11.5% (3/26)	13.6% (3/22)	7.1% (12/170)
Did not respond at all, despite multiple requests	18.2% (10/55)	20% (7/35)	30.8% (4/13)	31.6% (6/19)	3.8% (1/26)	13.6% (3/22)	18.2% (31/170)
Contact information could not be found or did not contact	0% (0/55)	40% (14/35)	0% (0/13)	0% (0/19)	19.2% (5/26)	50% (11/22)	17.6% (30/170)

Table 1: *Response to the Census.* The table above shows how the census was received and addressed by the six different groups of institutions and collectors. In total only 57% of curators and collections managers were able to provide accurate numbers for associated and/or articulated skeletons and reasonably accurate numbers for isolated bones and teeth.

institutions where language barriers prevented a proper review of the website. Some of these had online data and others did not. A few from this group surprisingly involved "science centers", where research and collections were obviously not the main priority. Here, locating contact information for curators, collections managers or even museum directors was often a long and futile search. Calls to front desk personnel were often disconnected or not even answered. Several locations eventually provided a name of someone to contact, but these calls were seldom returned.

There were also several private collectors and/or commercial companies that were not directly contacted. In these cases, a detailed review of their isolated bones and teeth was beyond the scope of the project. Usually, website data, newspaper reports or discussions with colleagues or personal knowledge was sufficient to obtain a count of their major skeletons. In these cases, direct contact was unnecessary.

Public museums and universities had the highest number of fully functioning databases from which to review collections, but this was much lower than expected (see Table 2). Only 9 of the 55 institutions and universities (UWBM, LACM, USNM, NCSM, OMNH, SWAU, UCMP, UCM, and YPM) surveyed had an online database system that was reasonably up to date and fully functional at the time of the study. Each utilized a different format, using custom software, which often made it difficult to obtain a quick and easy count or comparison across platforms. Most of these were well designed, however, and searchable through different fields (by taxon, collection date, specimen type, rock formation, etc.). Of those surveyed, UWBM, UCMP, LACM, YPM and SWAU stood out as providing the most detail in the easiest and most aesthetic format. SWAU in particular, provided photographs, historical and geologic context for just about every specimen in the large and mostly complete database.

Six other public museums and universities (AMNH, CMNH, KU, UW, CMC, NDGS) had a database (or shared a database such as “Specify” or “IDigBio”), but based upon communications with the curator or collections manager in charge or personal knowledge of their programs, was mostly incomplete, much older, and out of date. These included many with older collections, where Hell Creek and Lance dinosaur specimens were not the emphasis of their current research (AMNH, CMNH, UW), to newer programs which have yet to catch up with the speed of collecting (CMC, KU, NDGS). In general, most of the top 15 searchable databases were at least 1-3 years behind their collection programs. This is certainly reasonable and expected as preparation work, proper taxonomic identification and cataloging usually takes significantly more time than field collection. Most of those surveyed had large collections of dinosaur specimens that were still in storage, awaiting preparation, involved in active research or awaiting cataloging.

Twelve others had reasonably complete databases from which a count was possible. These included ten from museums/universities in foreign countries (BSP, CMN, MANN, NHMUK, MNHN, NSM, ROM, TMP, NMW, and OUMNH), one from regional museums and non-profits (SRPD) and one private educational/commercial company (PARC). Of those from foreign institutions, the Canadian museums had the most user friendly and detailed databases, but often did not have much from the Hell Creek or Lance. Much of these collections were from the equivalent Scollard and Frenchmen Formations of Canada. Of particular note, the SRPD had a very complete and detailed online presence including photographs and detailed descriptions of each fossil.

The final collection is my own PaleoAdventures Research Collection (PARC) database specifically created for this paper (Figure 2). Website design, text, and data entry (for 800+ specimens) of this database took approximately four months (for two people- part-time) and was done with a budget of less than $2,000. This shows that an online presence for even private collections is not only possible, but affordable. The new PARC database at www.virtualdinosaurmuseum.com, was officially launched in February of 2018.

Thankfully, a large number of public institutions indicated that they were in the process of building or updating their own online databases as well. Museums with large collections of Hell Creek/Lance specimens that were currently in this process, included 15 others: BMNH, DMNS, TCMI, FMNH, DDM, MPM, MOR, RAM, SDSMT, TGM, USGS, UMMP, UCRC, UWGM, VMNH. Some, such as the Museum of the Rockies implied that this process was almost complete and they should be back online by 2018 (Personal communication, John Scanella, curator at MOR, 2018). Some have already made great strides toward this goal such as VMNH (Personal communication, Alex Hastings, curator at VMNH, 2018; Williams, 2018). Others are really just getting started.

As mentioned previously, the process of key entering data, is very slow. Many institutions (e.g. SDSMT, MPM) have a back log of hundreds of specimens, much of which has yet to be prepared or evaluated. With decreasing budgets, few paid staff and a reliance on volunteers, cataloging and key-entering specimens into a database is increasingly more and more difficult and, for some, of seemingly low priority. For many, the process of correctly identifying specimens is daunting. A lack of good, published descriptive papers (complete descriptions with abundant illustrations and photos- not just skull elements) and qualified personnel, able to properly identify specimens, often leads to either misidentifications (e.g. UWGM, personal communication, David Lovelace, 2018) or incomplete cataloging (e.g. RAM personal communication Andrew Farke, 2018).

Analysis of Online Databases

		Public Museums and Universities	Foreign Museums	Regional and Local Museums	Private Museums and Educational Companies	Private Collections	Commercial Collections (skeletons only)	Combined Totals for All Groups
A)	Percentage of groups that had a fully functioning online database	16.3% (9/55)	14.3% (5/35)	7.7% (1/13)	5.3% (1/19)	0% (0/26)	0% (0/22)	9.4% (16/170)
B)	Percentage of groups which had a database, but it was older or outdated	10.9% (6/55)	8.6% (3/35)	0% (0/13)	0% (0/19)	0% (0/26)	0% (0/22)	5.3% (9/170)
C)	Percentage of groups that had a database, but was currently offline or not working at the time of study	9.1% (5/55)	0% (0/35)	0% (0/13)	0% (0/19)	0% (0/26)	0% (0/22)	2.9% (5/170)
D)	Percentage of groups that had a database, but had very few, if any vertebrate fossils	5.5% (3/55)	5.7% (2/35)	0% (0/13)	0% (0/19)	0% (0/26)	0% (0/22)	2.9% (5/170)
E)	Percentage of groups that were currently building an online database	18.2% (10/55)	8.6% (3/35)	0% (0/13)	0% (0/19)	0% (0/26)	0% (0/22)	7.6% (13/170)
F)	Percentage of groups with no database, no apparent intent to build one or unknown intent	40% (22/55)	62.9% (22/35)	92.3% (12/13)	94.7% (18/19)	100% (26/26)	100% (22/22)	71.8% (122/170)

Table 2: *Analysis of Online Collections Databases*. The table above shows the availability of online collections databases during the 2017-2018 Hell Creek/Lance Dinosaur Census. Only 9.4% had a fully functioning collections database from which to view. This includes only 16.3% of public institutions. A surprising 71.8% of groups known to possess Hell Creek or Lance dinosaur remains, had absolutely no online database that could be found.

For many collections managers and curators, the process of building and populating a database is simply overwhelming. For others, research projects trump what may be considered a "book keeping" chore. Many may not like their collections programs, lab work or research publicly scrutinized. Several, on the private collection side, expressed concerns about sharing their collections publicly, for fear of theft, reprisals or criticisms from academics or potential confiscation by the federal government if collection laws suddenly changed. Whatever the reasons, a total of 71.8% of all known Hell Creek and Lance Formation dinosaur collections had absolutely no online collections database whatsoever. Sadly, this included at least 40% of the surveyed public museums and universities in the USA. In a time where open source access to contextual data is the rising trend and professed academic desire, this should improve soon.

Analysis of Exploration Programs

		Public Museums and Universities	Foreign Museums	Regional and Local Museums	Private Museums and Educational Companies	Private Collections	Commercial Collections (skeletons only)	Combined Totals for All Groups
A)	Current, Active exploration program in HC/Lance Fm. (2017-2018)	32.7% (18/55)	5.7% (2/35)	53.8% (7/13)	52.6% (10/19)	23.1% (6/26)	81.8% (18/22)	35.9% (61/170)
B)	Past program at least within the last 10 years	10.9% (6/55)	0% (0/35)	23.1% (3/13)	15.8% (3/19)	0% (0/26)	13.6% (3/22)	8.8% (15/170)
C)	Past program at least within the last 25 years	20% (11/55)	8.6% (3/35)	0% (0/13)	0% (0/19)	11.5% (3/26)	0% (0/22)	10% (17/170)
D)	Past program at least within the last 100 years	21.8% (12/55)	0% (0/35)	0% (0/13)	0% (0/19)	0% (0/26)	0% (0/22)	7.1% (12/170)
E)	They do not have a dig themselves, but assist on another groups digs	1.8% (1/55)	0% (0/35)	0% (0/13)	5.3% (1/19)	53.8% (14/26)	0% (0/22)	9.4% (16/170)
F)	Has never actively dug in the HC/Lance. All specimens acquired through donation, sale or trade	12.7% (7/55)	85.7% (30/35)	23.1'% (3/13)	26.3% (5/19)	11.5% (3/26)	4.5% (1/22)	28.8% (49/170)

Table 3: *Analysis of Hell Creek/Lance Exploration Programs.* Even though a comprehensive analysis of collection programs was beyond the scope of this paper, some data could be interpreted. At least 61 groups are currently exploring the Hell Creek and Lance Formations for dinosaur remains.

II. An Analysis of Collection Programs:

Even though a comprehensive historical review of exploration programs was beyond the scope of this project, certain observations as such were able to be obtained. Based upon the new census, (see Appendix 2 and Table 3) there are at least 61 groups currently collecting dinosaur fossils from the Hell Creek and the Lance Formations (2017-2018). These included, 18 known public museums and universities from the USA, 2 foreign museums, 7 regional museums and non- profits, 10 private museums, science centers, large scale commercial groups or educational companies, at least 6 private collectors and 18 smaller, exclusively commercial collectors. 44% (27/61) of these were essentially public groups and 56% (34/61) were predominantly private, continuing the increased trend and relevance of private collection over the last 30 years. There are also, no doubt, a few groups, private ranchers, private collectors and commercial collectors working their own sites that were not located, so the actual total number of groups currently working in the Hell Creek/Lance is more than likely a bit higher.

Analysis of Hell Creek/Lance Exploration Programs from Online Databases- Public Museums Only

(Not Counting Purchases or Donations)

	Last Known Expedition	Most Recent Collection Event Recorded in Database	Dates of known Major Expeditions or Collection Events to the Hell Creek and/or Lance Formations
AMNH	N/A	N/A	1900-1902, 1904-1906, 1908-1910, 1916, 1928, 1931, 1939, ?
UWBM	2017	2017	1960,1968,1971,1986-1988,1997, 2001-2003, 2007-2017
CMNH	1978	1978	1900, 1902, 1904, 1906, 1938, 1977-1978,
CMC	2017	2015	2012 - 2017
LACM	N/A	2007	1965-1970, 1972, 1974, 2001-2007
MOR	2017	N/A	1980's-present?; 1999-2010 (Hell Creek Project)
USNM	N/A	1987	1856-1857, 1887, 1889-1893, 1908-1910, 1920 ,1939, 1973, 1987?
NCSM	2017	N/A	1993, 1998-1999, 2007, 2016-2017
NDGS	2017	N/A	1980's? to present
RAM	2001	2001	1992-2001
OMNH	N/A	N/A	1935
SWAU	2017	2016	1992-2017
KU	2017	2015	1895, 1971-1972, 2002, 2008-2017
UCMP	N/A	2006	1956-1958, 1970, 1975-1977, 1979-1980, 1982-1987, 1989-1996, 1998, 2000, 2002-2003, 2006,
UCM	N/A	N/A	N/A
UW	N/A	N/A	1950's-1960's; sporadic since
USGS	N/A	N/A	1870's, 1920's-1930's
VMNH	N/A	N/A	Expeditions were conducted by the now defunct Shenandoah College
YPM	2010	2010	1889-1892, 1895,1918, 1929-1930, 1948-1950, 1961-1962, 1964, 1971, 1978, 2009-2010

Table 4: *A Brief Review of Major Expeditions to the Hell Creek by Public Institutions (USA only-with Databases only)*. The table above shows nineteen of the public repositories in the USA that are known to have extensively explored the Hell Creek and the Lance throughout the last 130 years. Expedition years were determined either by review of the collections database, personal contact with the curator in charge, review of literature (Clemens and Hartman, 2014) or personal knowledge of the program. Additional years are likely, but unknown and not reflected by accessioned specimens in the database.

Another 32 groups are no-longer working in the Hell Creek/Lance, but did have significant activity within the last 25 years. This included 17 public museums and universities, three foreign museums, three regional or non-profits, three private museums, science centers and educational companies, three private collectors and three exclusively commercial collectors. Certain public groups have changed their research focus and are no longer collecting, while others have not been able to afford the high costs of exploration programs, crippled by budget cuts. Some of the private groups/collectors that are no longer working have since retired or gone out of business. Other groups have since taken over many of those sites and continue digging today.

Interestingly, over 38% of those polled have never had a field program themselves. These either assisted other groups on their sites or have acquired their specimens via trade, donation or sale. This included over 12% (7/55) of the public museums in the USA, 85% (30/35) of the foreign museums, and 23% (3/13) of the local or regional museums. Foreign museums clearly have been the primary beneficiary and final destination for many of the privately collected specimens in the Hell Creek and Lance over the last 50 years. An extensive review of specimens collected by private groups and sold to museums in Europe or Asia can be found in Winters (2014). A total of at least 55 dinosaur skulls and skeletons (28 ceratopsids, 19 hadrosaurids, two thescelosaurids, one pachycephalosaurid, one ankylosaurid and four tyrannosaurids) and some 4,000 isolated bones and teeth are now in foreign museums, many of which were originally discovered, prepared and sold by private sources.

Additional information regarding the total number of seasons the top groups with databases have spent in the field, can be found in Table 4. Hopefully, additional, more comprehensive surveys, will be able to discern the total number of "field-years" spent collecting the Hell Creek and Lance Formations for all of the current and former groups, but this is for another paper.

III. An Analysis of the Combined Hell Creek and Lance Formation Dinosaur Collections:

The complete results of the new census can be found in the attached Appendix 1 and 2 of this paper. Quick summaries can be found in Tables 5, 6, 7, 8 and 9. At least 653+ associated and/or articulated, skulls and/or skeletons were located in the 170 known Hell Creek/Lance dinosaur collections (Table 5 and 6). Of those, 441, or 67.5% of the total, were presently in public institutions within the United States. The remaining 32.5% of associated and/or articulated specimens were located as follows: 55 in foreign museums, 65 in local museums/non-profits, 55 in private museums and educational companies, 9 in known private collections and 28 in known, exclusively commercial collections. As mentioned previously, most of the specimens currently housed in foreign museums were acquired via trade, sale or donation. Most of these were originally collected by private commercial interests (Winters, 2014).

Analysis of Total Collected Dinosaur Specimens

	Public Museums and Universities	Foreign Museums	Regional and Local Museums	Private Museums and Educational Companies	Private Collections	Commercial Collections (skeletons only)	Combined Totals for All Groups
Total number of associated or articulated skeletons and/or skulls	441+	55+	65+	55+	9	28+	653+
Total number of estimated isolated bones and teeth	25,251++	3,988+	4,054++	4,059++	4,506++	N/A	41,858++

Table 5: *Summary Table for Both Associated and/or Articulated Specimens and Isolated Specimens.* A grand total of 653 associated and/or articulated skulls and skeletons were located in the 170 known collections. Over 41,800 isolated bones and teeth were also located. Many smaller collections were privately held and not counted and it is likely some specimens were not located. As such, these should be considered the minimum numbers rather than actual numbers.

Total # of Associated and/or Articulated Specimens by Family

(Isolated skulls, skulls and skeletons, fragmentary to complete)

	Ceratopsidae	Hadrosaur-idae	Thescelosaur-idae	Pachycephalo sauridae	Ankylosaur-idae & Nodosauridae	unknown ornithischians	Tyrannosaur-idae	Ornitho-mimidae	Oviraptoro-sauridae	Dromaeosaur-idae & Troodontidae	Unknown or Other Theropods
Public Universities and Museums	237+	96+	29+	12+	7+	0	43+	9+	6+	0	2+
Regional Museums & Not-for-Profits	39+	17+	4+	2+	0	0	2+	0	1	0	0
Foreign Universities and Museums	28+	19+	2+	1+	1+	0	4+	0	0	?	0
Private Museums & Educational Groups	19+	11+	5+	1+	2+	0	11+	3+	2+	1+	0
Private Collections	2+	4+	0	0	1+	0	2+	0	0	0	0
Commercial Collections	10+	2+	2+	2+	1+	0	9+/-	1+	0	1+	0
TOTALS:	335+	149+	42+	18+	12+	0	71+	13+	9+	2+	2+

Table 6: *The Total Number of Associated and/or Articulated Specimens By Family of Dinosaur.* This table shows each of the major categories of dinosaur and the number of specimens held by each of the collection types. Ceratopsid skeletons and skulls dominated the dataset.

At least 65 associated and/or articulated specimens were located in regional museums or non-profit entities, but many of these will be switched to a public repository soon. According to personal communications with Tyler Lyson and Joe Sertich (2017), the bulk of the Marmarth Research Foundation collection, including over 25+ associated and/or articulated remains, will be transferring to the Denver Museum of Nature and Science in the coming year. Once this transfer is complete it will increase the total associated and/or articulated skulls/skeletons in US Public Institutions, by another 3-4 percent.

Public vs. Private

(Associated and/or Articulated Specimens Compared)

	Ceratopsidae	Hadrosaur-idae	Thescelosaur-idae	Pachycephal-osauridae	Ankylosaurs & Nodosaurs	unknown ornithischians	Tyrannosaur-idae	Ornitho-mimidae	Oviraptoro-sauridae	Dromaeosaur-idae & Troodontidae	Unknown or Other Theropods	TOTAL
MOSTLY PUBLIC	276 (54.5%)	113 (22.3%)	33 (6.5%)	14 (2.8%)	7 (1.4%)	0 (0.0%)	45 (8.9%)	9 (1.8%)	7 (1.4%)	0 (0.0%)	2 (0.4%)	506+ (77.5%)
MOSTLY PRIVATE	59 (40.1%)	36 (24.5%)	9 (6.1%)	4 (2.7%)	5 (3.4%)	0 (0.0%)	26 (17.7%)	4 (2.7%)	2 (1.4%)	2 (1.4%)	0 (0.0%)	147 (22.5%)
TOTALS:	335 (51.3%)	149 (22.8%)	42 (6.4%)	18 (2.8%)	12 (1.8%)	0 (0.0%)	71 (10.9%)	13 (2.0%)	9 (1.4%)	2 (0.3%)	2 (0.3%)	653

Table 7: *Public Vs. Privately Held Specimens.* This table shows a comparison between specimens held by predominantly public institutions vs. those held by predominately private institutions. Privately collected specimens included at least 147 skulls/skeletons or 22.5% of the tallied collection.

Of the 441 associated and/or articulated, specimens in public institutions in the USA (Figure 3), 237 are ceratopsids (53.7%), 96 are hadrosaurids (21.8%), 43 are tyrannosaurids (9.8%), 29 are thescelosaurids (6.6%), 12 are pachycephalosaurids (2.7%), 9 are ornithomimids (2.0%), 7 are ankylosaurids or nodosaurids (1.6%), 6 are oviraptorosaurids (1.4%) and 2 specimens are of unusual small theropods (0.4%). There are no reported, associated or articulated dromaeosaurid or troodontid specimens known from any of the 55 public institutions in the USA.

Privately collected associated and/or articulated specimens also produced interesting ratios (Table 7). Private museums, science centers, educational companies, private collections, commercial collections and specimens mostly sold to foreign museums include at least 148 known associated and/or articulated specimens. This includes: 59 ceratopsids (39.9%), 36 hadrosaurids (24.3%), 9 thescelosaurids (6.1%), 4 pachycephalosaurids (2.7%), 5 ankylosaurids or nodosaurids (3.4%), 27 tyrannosaurids (18.2%), 4 ornithomimids (2.7%), 2 oviraptorosaurids (1.4%), and 2 dromaeosaurids/troodontids (1.4%). Here, most of the ratios between public and privately collected specimens are similar, except for the obvious collection and purchase bias towards tyrannosaurs.

Of the 653 total associated and/or articulated specimens located (Table 6 and Figure 4), there are 335 ceratopsids (51.3%), 149 hadrosaurids (22.8%), 71 tyrannosaurids (10.9%), 42 thescelosaurids (6.4%), 18 pachycephalosaurids (2.8%), 13 orthithomimids (2.0%), 12 ankylosaurids or nodosaurids (1.8%), 9 oviraptorosaurids (1.4%), 2 dromaeosaurids or troodontids (0.3%), and 2 indeterminate small theropods (0.3%). Despite these substantial numbers it is important to understand, that many of these specimens are fragmentary, consisting of less than 10% of the entire animal. The vast majority of these articulated and/or associated remains consisted of isolated skulls or portions of skulls, partial skeletons or loosely associated elements. Skeletons exceeding the 50% complete threshold were quite rare. Of particular note, 85% of all known associated and/or articulated remains came from just three families of dinosaur; Ceratopsidae, Hadrosauridae and Tyrannosauridae. Specimens of these families were dominated by the three most commonly recovered genera, adult or subadult specimens of *Triceratops*, *Edmontosaurus* and *Tyrannosaurus*. All three of these genera are extra large-bodied taxa whose adult weights exceeded 2,000 kg. and whose skeletal elements are large, robust and resistant to weathering (Table 8- adapted from Brown et al., 2012 and Figure 5). The only exception to this are the ankylosaurids and nodosaurids which are also in the extra-large-bodied size ranges, but whose specimens made up a mere 1.8% of the total collected specimens.

Associated and/or articulated remains of *Triceratops* are, by far, the most frequently discovered and collected genera by a wide margin. Over 325 associated and/or articulated specimens of *Triceratops* were located representing over 50% of all available skulls/skeletons collected from the Hell Creek and the Lance. According to various reports, numerous additional specimens of *Triceratops* were frequently discovered, but not collected (Pearson et al., 2002; White et al., 1998; Horner et al., 2011; Scannella and Fowler, 2014) or were discovered and may have disappeared into private collections (Clemens and Hartman, 2014). Mature, adult and sub-adult sized individuals were by far the most common. Juvenile skulls and skeletons, on the other hand, were quite rare consisting of only a few reported good specimens.

Associated and/or articulated remains of *Torosaurus* by comparison were significantly much rarer. Only seven skulls and/or partial skeletons were found in Hell Creek or Lance collections (plus a few others in Denver/Laramie/Frenchman and North Horn Fm.) (Longrich and Field, 2012; McDonald et al., 2016). Due to the similarities between *Triceratops* and *Torosaurus* post-cranial elements it is highly likely that there were other specimens of *Torosaurus* present, but these were not properly identified in the databases. Regardless of this possibility, identified remains of ceratopsids split 97% *Triceratops* to 2.1% *Torosaurus*, with the remainder a few isolated skulls referred to *Leptoceratops, Nedoceratops* and *Tatankaceratops* (Ott, 2006; Ott and Larson, 2010; Farke, 2011). Scanella and Horner (2010), suggested that the name

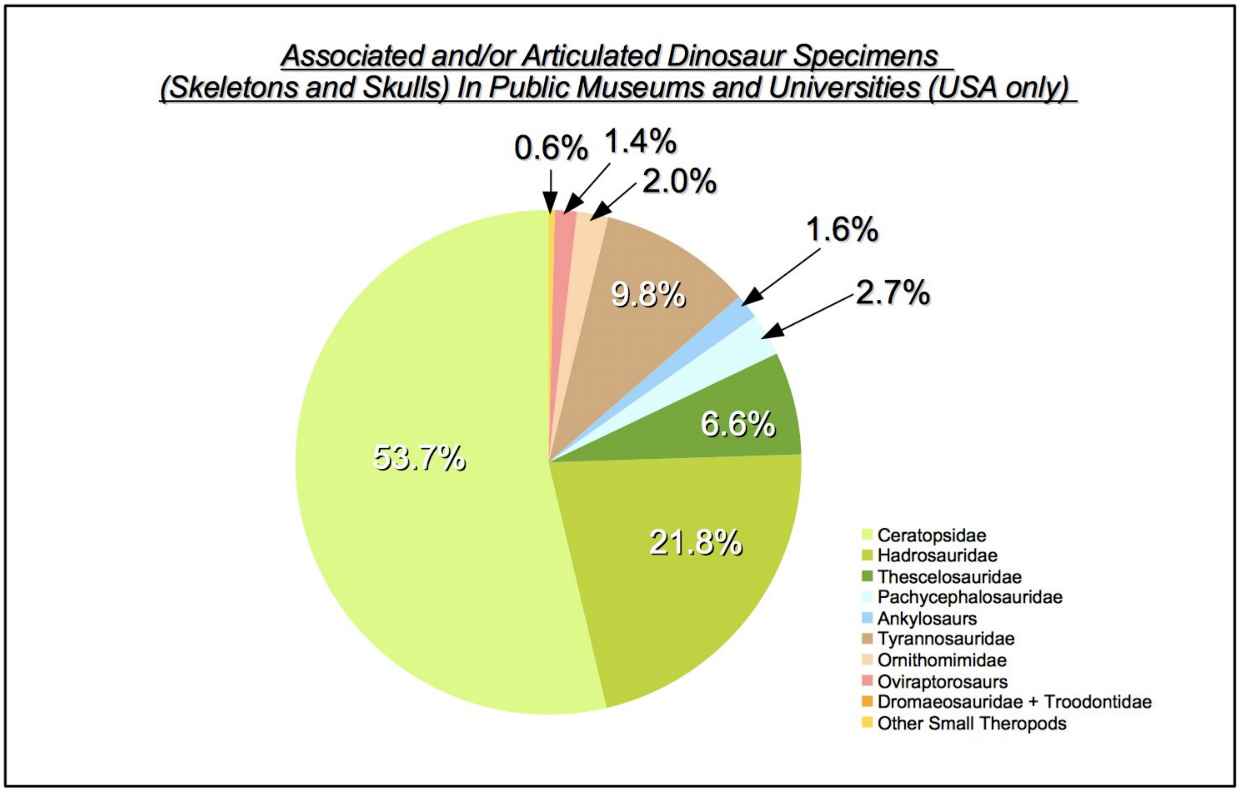

Figure 3: *Associated and/or Articulated Dinosaur Specimens by Family within 55 Public Universities and Museums in the USA.* Associated and/or articulated specimens in the public domain were dominated by ceratopsids (53.7%), hadrosaurids (21.8%) and tyrannosaurids (9.8%). The only other group with a large number of associated/articulated remains were thescelosaurids.

Torosaurus was invalid and specimens referred to it were merely mature individuals of *Triceratops*. If this were the case, one would expect a much higher percentage of *Torosaurus* in the total collection for any normalized population as well as clear transitionary forms. The presence of smaller and younger specimens of *Torosaurus* as well as distinct features unique to it (Farke, 2011; Longerich and Field, 2012) suggest that it is indeed a valid taxon. If so, these low numbers suggest that it was a much rarer dinosaur in the Hell Creek/Lance ecosystem.

A similar, but reversed discrepancy exists within the tyrannosaurids, between *Tyrannosaurus* and *Nanotyrannus*. Specimens referred to as *Tyrannosaurus* included at least 67 known specimens from the Hell Creek and Lance (more from other units such as the North Horn, Scollard, etc.), which ranged from highly fragmentary remains (DMC- partial articulated leg) to mostly complete skulls and skeletons (90% complete Sue- FMNH-PR2081) (Larson, N., 2008). The majority of these were less than 25% complete. Most were from mature, adult specimens exceeding an estimated 6,000kg in live weight and 30 feet in estimated length. Articulated and/or associated specimens, argued to be either juvenile *Tyrannosaurus* (three specimens), or *Nanotyrannus* (an additional six specimens), were less than 12.7% of all tyrannosaurids and less than 1.4% of the total available dataset Unfortunately, many of the specimens that might shed light on this question ("Tinker", "Baby Bob" and/or the "Dueling Dinosaurs Theropod") are not accepted by academics as they are currently in private hands. Other specimens are highly fragmentary (LACM 28471 formerly referred to as the "Jordan Theropod") or just skulls (CMNH 7541). Some are slightly more complete, but largely ignored (SWAU or WPB specimens). The best young

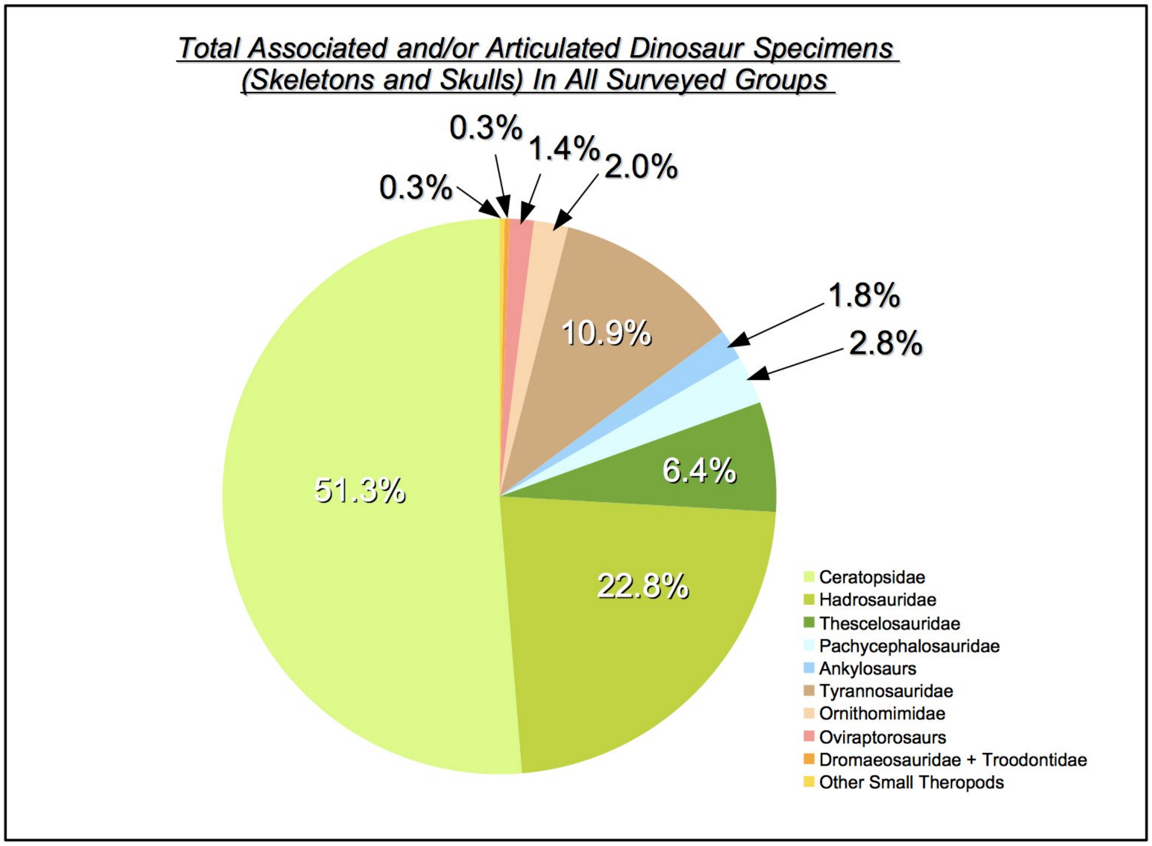

Figure 4: *Associated and/or Articulated Dinosaur Specimens by Family Across all 170 Groups.* The graph above shows the relative percentages of all known specimens recovered from the Hell Creek and Lance Formations. Associated and/or articulated remains are dominated by only three groups... ceratopsids, hadrosaurids and tyrannosaurids. Of these, *Triceratops* was the most commonly recovered genera with over 325 known associated and/or articulated skeletons and skulls.

Tyrannosaurus/*Nanotyrannus* is, of course, BMR P2002.4.1 also known as "Jane", but the lack of a large dataset for comparative purposes leaves many ontogenic questions unanswered. Until multiple, definitive *Tyrannosaurus* specimens younger than Jane or definitive *Nanotyrannus* older than Jane are found and studied, the debate is mostly moot. Hopefully, a newly discovered specimen, discovered by the University of Kansas crews in 2017, will help shed some light on this issue (personal communication, David Burnham, 2018). A detailed review of the debate on the validity of *Nanotyrannus* is beyond the scope of this paper (please see: Larson, P., 2008; Carr, 1999 etc.), but if *Nanotyrannus* is a valid taxon (and many characters suggest that it is), it was likely a much rarer component of the Hell Creek and Lance ecosystem or at least preferred a sub-environment further upland or away from the main river channels that was not conducive for preservation. Based upon the large quantities of isolated, shed *Nanotyrannus* teeth found throughout channel lags and micro-sites of the Hell Creek and the Lance, the latter is more than likely the case.

Associated and/or articulated specimens in the large-bodied class (200-2,000 kg) (Body mass estimates modified from Paul, 2010; 2011; Brown et al., 2012; Gorman and Hone, 2012; Campione et al., 2014), included eight additional genera; *Anzu, Thescelosaurus, Struthiomimus sp., Dakotaraptor*, *Pachycephalosaurus*, *Stygimoloch* and the enigmatic *Nedoceratops* and *Tatankaceratops*. Of these, *Thescelosaurus* is the only one based on a large sample set (42) of reasonably complete, articulated skeletons. This high number suggests that it was a major component of the Hell Creek/Lance ecosystem.

Hell Creek and Lance Genera Ranked by Estimated, Average Adult Mass

Size class (modified from Brown et. al., 2012)	Modern Analogs By Size	GENERA (28 genera +/-)	Estimated Mass (kg)	Total # of associated and/or articulated specimens	Percent % (653 specimens)
Small-bodied genera (non-avian) (<60kg)		*Avisaurus (but... aves most likely)*	N/A	2?	**0.6%** (4/653)
		Pectinodon	10?	0	
	Secretary Bird (10kg)	*Richardoestesia (gilmorei)*	15?	0	
		cf. Saurornitholestes	20	0	
		cf. Albertonychus	25?	0	
		Sphaerotholus	30?	0?	
		Paronychodon/Zapsalis	35?	0	
		undescribed *oviraptorosaur*	40?	2	
	Emu (40 kg)	*possible undescribed basal ornithopod?*	50?	0	
		possible undescribed *dromaeosaur?*	50?	0	
Intermediate-bodied genera (60-200kg)		*Acheroraptor*	60?	0	**0.5%** (3/653)
	Cassowary (80 kg)	*cf. Troodon*	60	1	
		Leptorhynchos	60?	0	
	Ostrich (110 kg)	*Dracorex*	100?	1	
		Leptoceratops	190	1	
Large-bodied genera (200-2,000 kg)		*Anzu*	200	7	**13.2%** (86/653)
		Struthiomimus sp.	200 - 300	13	
	American Bison (600 kg)	*Thescelosaurus*	275 - 300	42	
		Dakotaraptor	350 – 450	1	
		Pachycephalosaurus/ Stigimoloch	400 – 500	17	
		Nanotyrannus	1,000 - 1,500	4+/-	
		Tatankaceratops	1,500-2,000?	1	
		Nedoceratops	1,500-2,000?	1	
Extra large-bodied genera (2,000 kg +)		*Denversaurus*	2,000 - 3,000	6	**85.8%** (560/653)
	White Rhino (2,300 kg)	*Ankylosaurus*	3,000 - 5,000	6	
		Edmontosaurus	3,000 - 5,000	149	
	African Elephant (3,000-6,000 kg)	*Tyrannosaurus*	6,000 - 9,000	67+/-	
		Triceratops	6,000 - 10,000	325+	
		Torosaurus	6,000 - 11,000	7	

Table 8: *Hell Creek/Lance Fm. Genera Sorted by Estimated Mass (adapted from Brown et. al., 2012)*. The table above shows that the vast majority of specimens collected in the Hell Creek and Lance are from extra-large bodied forms. Large bodied forms are also rare, with the exception of Thescelosaurus. Skeletons of taxa under 200 kg are mostly absent. (Body mass estimates modified from Paul, 2010; 2011; Brown et. al., 2012; Gorman and Hone, 2012; Campione et. al., 2014).

Had it been a larger dinosaur we most likely would have even more specimens of it. Some, like Derstler (1994), have even suggested that Thescelosaurus may have been the most common dinosaur in the ecosystem and that it's lower rate of discovery is merely a product of taphonomic bias. *Pachycephalosaurus* and *Stygimoloch* (differences most likely due to sexual dimorphism in *Pachycephalosaurus*) combined for a total of 17 associated and/or articulated specimens, but this number is actually quite deceptive. Pachycephalosaur material from the Hell Creek and Lance consisted of mostly isolated fronto-parietal domes, with little or no associated post-cranial material. Good skulls, consisting of at least 50% of all skull elements, tallied only five specimens (AMNH 1696, VRD 13, DMNS 469, BHI 126376, and TPI/NSM?) and only one of these had a significant portion of post-cranial elements associated with it ("Sandy" now at the NSM in Japan). Two other specimens, (UCMP 128383 and AMNH 21542) included both a "partial skull & skeleton", (Horner and Goodwin, 2009), but the material is far from 50% complete and these were originally referred to as *Stygimoloch*. To my knowledge there has never been any articulated pachycephalosaur material found in either formation. The Hell Creek ornithomimid (*Struthiomimus sp*/*Ornithomimus*?) shares similar issues. It included a fair number of good skeletons, but significantly lower numbers when compared with other ornithomimid genera in earlier rock units. Additional, well preserved specimens and detailed reviews of this unassigned ornithomimid are needed to understand its true taxonomic affinities.

The large bodied *Anzu* and *Dakotaraptor* are also problematic in the available dataset. Both of these specimens were unknown up until the early 2000s and were not described until 2014 and 2015 respectively (Lammana et al., 2014; Depalma et al., 2015). Whereas we now have a few good specimens of *Anzu* in that 30-65% complete range, most are known from fragmentary, associated skeletons with no articulation. *Dakotaraptor* is based upon just a single 10% skeleton, missing the skull. The lack of a large complete dataset for either genera presents a significant challenge to anyone attempting to assess their morphologic variation, affinities to other taxa or role in the ecosystem. Their presence is clear, but creates many more questions than answers.

Associated and/or articulated dinosaur specimens under the 200kg estimated size range (Body mass estimates modified from Paul, 2010; 2011; Brown et al., 2012; Gorman and Hone, 2012; Campione et al., 2014), were nearly absent from the fossil record. These included several suspected dromaeosaurids, troodontids, oviraptorosaurids, alvarezsaurids, basal ornithopods and pachycephalosaurs. What little knowledge we have of these animals is based primarily on shed teeth and isolated remains. There are only seven specimens that are of any completeness to qualify as an associated and/or articulated specimen. This includes the single skull and three cervical vertebrae of *Dracorex* (Bakker, 2006), a partial skull of *Leptoceratops* (Ott, 2006), a partial, articulated lower leg of *Troodon* (privately held- personal communication Matt Wirt, 2017), two partial, undescribed oviraptorosaurs in a single block (personal communication Pete Larson, 2016), a specimen of unknown affinity (which might be a database error- DMNS) and a single fused tarsometatarsus of *Avisaurus* (Brett-Surman and Paul, 1985), which is most likely an enantiornithine bird and not a non-avian dinosaur (Varricchio and Chiappe, 1995). The only other specimen that has been considered "associated" is a maxilla and dentary of *Acheroraptor* which were found in a channel lag four meters away from one another (Evans et al., 2013). Since this specimen consists of only two widely spaced elements it failed to meet the 1% guideline set up to qualify as associated and/or articulated remains.

Brown et al. (2012), found similar patterns of discovery, regarding size, within the fauna of the Dinosaur Provincial Park Formation. Their analysis suggested that there was a strong correlation between a taxon's estimated adult size and the number of good specimens recovered. Their study showed a strong collection and taphonomic bias towards larger-bodied forms. They found that larger-bodied dinosaurs were usually well represented by numerous, mostly complete, articulated and associated skulls and skeletons, whereas smaller bodied forms were based primarily on isolated remains or teeth. They concluded that these inherent collection and taphonomic biases must be considered when attempting to understand the diversity

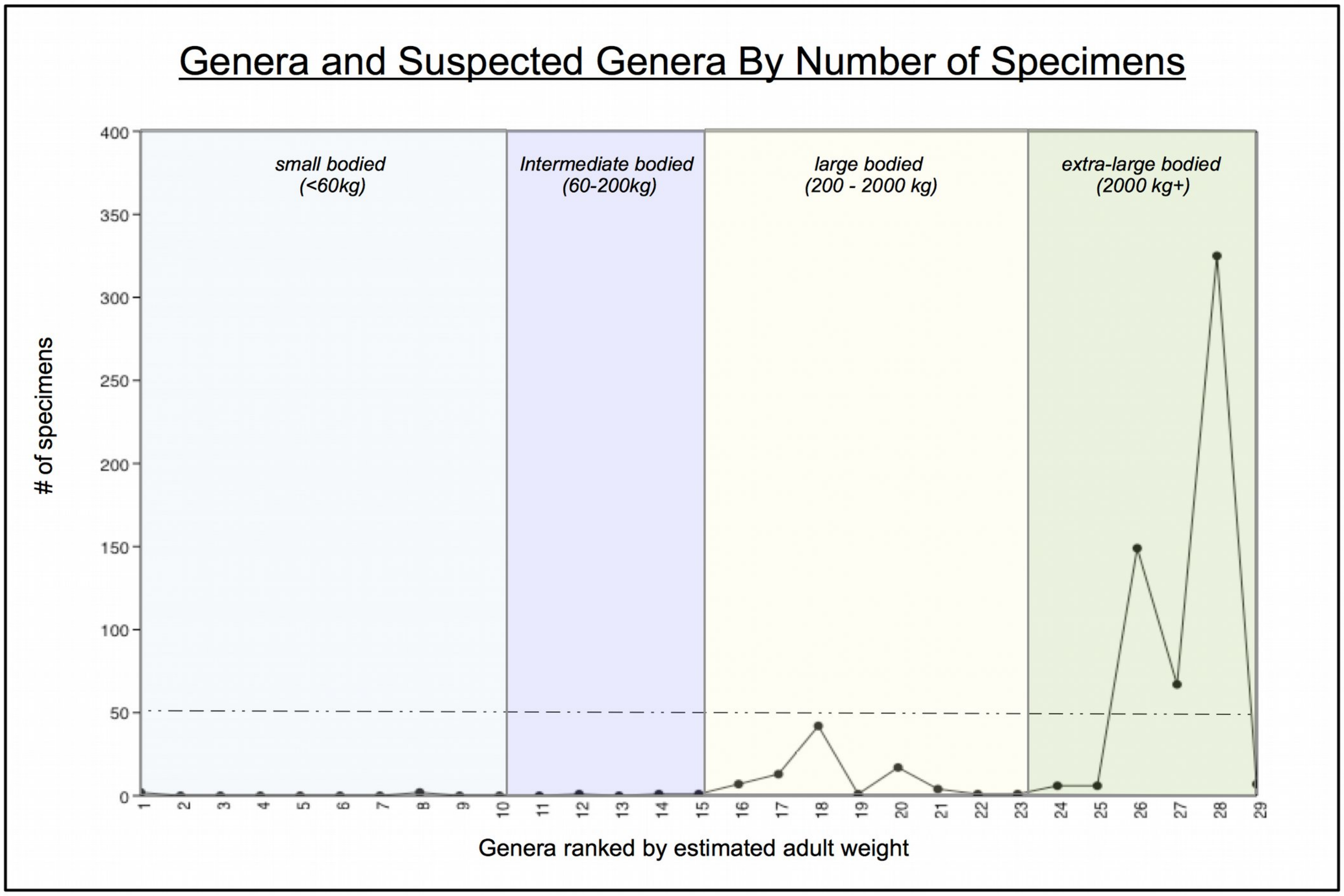

Figure 5: *Graph of genera ranked by estimated weight vs. number of specimens*. Census numbers for genera and suspected genera when ranked by estimated mass and graphed by number of specimens clearly shows a bias towards genera in the extra large bodied size class. If we assume a minimum threshold of 50 specimens/genera for accurate understanding of the ecosystem's population and diversity we see that only three genera meet this criteria (#26- Edmontosaurus, #27- Tyrannosaurus and #28 Triceratops) and only one comes close (#18 Thescelosaurus). All others fall well below this mark, including all genera under 200 kg. Including controversial taxa within widely accepted taxa does nothing to correct this bias.

of any ancient ecosystem.

The vast number of specimens recovered in the 2017-2018 Hell Creek/Lance Fm. census came from just three genera, each well over 2,000 kg of adult live weight (Table 8 and Figure 5). If we assume that a baseline minimum of at least 50 specimens is needed (modified from Steinsaltz and Orzak, 2011), to confidently address questions of population, ecology, diversity and variation we see that only *Triceratops*, *Edmontosaurus* and *Tyrannosaurus* meet this criteria. Only one additional genera, *Thesecelosaurus* (42) comes close. Everything else falls considerably short.

A rarefaction curve (See figure 6) for ranked genera with articulated or associated material show a curve that is nowhere near an asymptope, suggesting that the available database is insufficient for many studies. A Chao-1 calculation, however, extrapolates the possibility of at least 24 genera expected. This fits with the observed isolated bones and teeth numbers which indicates the presence of several additional genera and suspected genera. Additional statistical tests and metrics need to be applied in future papers to address these results.

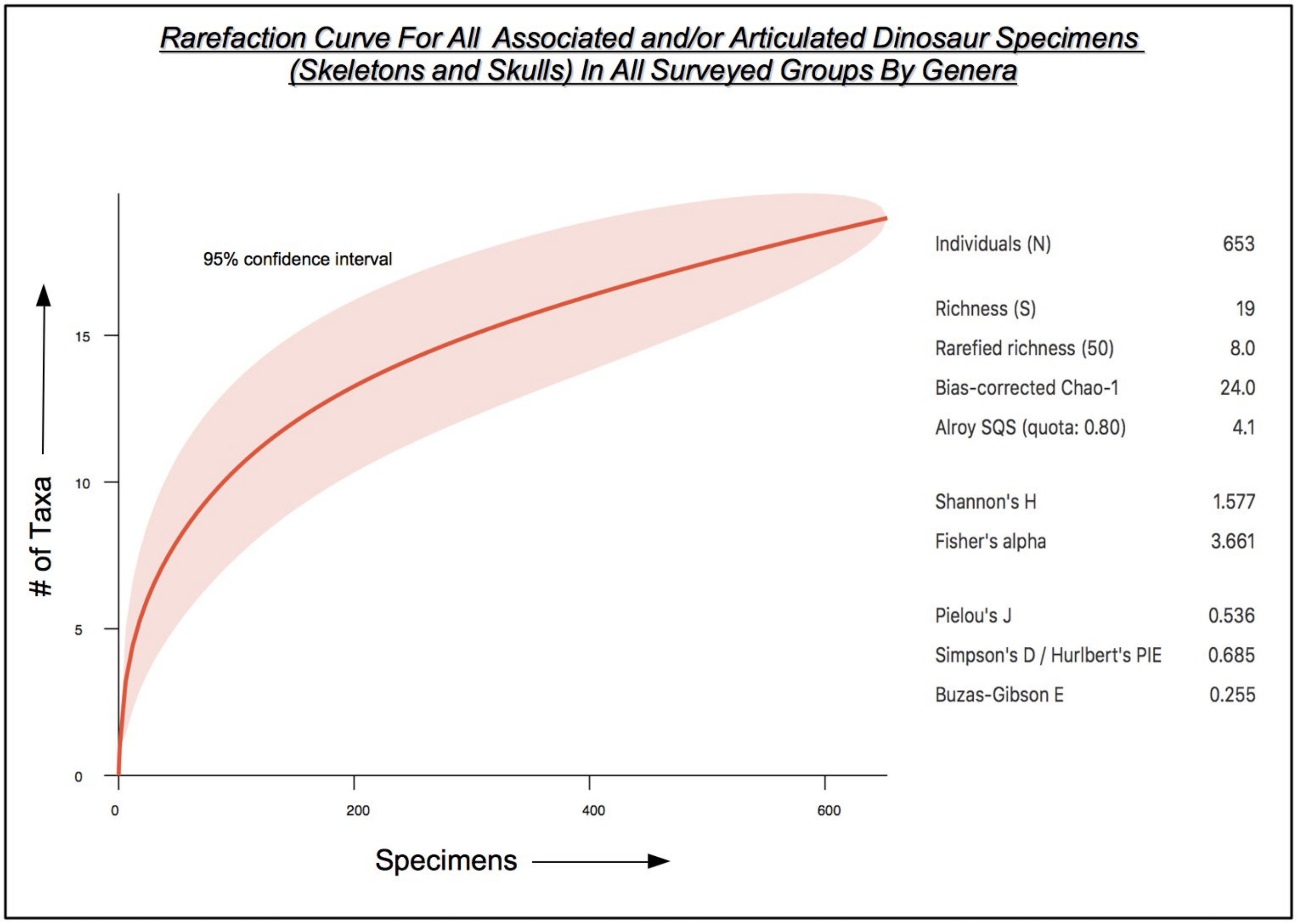

Figure 6: *Rarefaction Curve for the Hell Creek and Lance Dataset*. Dinosaur genera which had at least one known associated and/or articulated skull or skeleton, were then ordered and entered into the application known as "Taxon 1.0.1". This produced a rarefaction curve with a gently climbing slope that was not near asymptope. Evenness (Simpson's D/Hurlberts PIE) was considerably lower than 1, suggesting probable bias within the collection. Extrapolated Chao-1 numbers estimate that at least 24 genera are likely to be found given enough time and additional sampling. This implies that there is still much more field work that needs to be done in the Hell Creek and the Lance to truly understand this complex ecosystem.

With regards to isolated bones and teeth, hadrosaurids (*Edmontosaurus* mostly*)* were by far the most frequently found and collected (Table 9 and Figure 6). This can be attributed directly to collection and preservation bias, as much of these remains have been collected from mono-specific bone beds, in fluvial channel or crevasse-splay deposits. At least five, large-scale, *Edmontosaurus* dominated bone beds are known from this record ["Concordia Quarry"- SRPD (Ullman et al., 2017); "Ruth Mason Quarry"- BHI and TCMI; "Hanka Quarry"- DMNS and WDC; "SWAU quarries" (personal communication, Keith Snyder, 2017); and the "Ruby Site"- SDSMT-Dinosaurs and More (Personal communication Gary Olson, 2014)]. These sites include large quantities of disarticulated remains of *Edmontosaurus* almost exclusively. They indicate multiple animals, from adult to juvenile, most likely attempting to cross a river during flood stage and failing. Subsequent decay and scavenging, followed by fluvial transport then deposited and concentrated these elements en masse.

Triceratops isolated elements, skulls, and associated and/or articulated remains, on the other hand,

Total # of Isolated Elements and Teeth by Family

	Ceratopsidae	*Hadrosaur-idae*	*Thescelosaur-idae*	*Pachycephalo sauridae*	*Ankylosaur-idae & Nodosauridae*	*unknown ornithischians*	*Tyrannosaur-idae*	*Ornitho-mimidae*	*Oviraptoro-sauridae*	*Dromaeosaur-idae & Troodontidae*	*Unknown or Other Theropods*
Public Universities and Museums	4,342++	11,332 +/-	440+	170+	169+	1,494+	785+	280+	22+	1,167+	3,399+
Regional Museums & Not-for-Profits	888+	2,717++	54+	2+	2+	2+	155+	22+	12+	43+	146+
Foreign Universities and Museums	1,340++	38++	5+	13+	6+	2+	41+	9+	14+	16+	1+
Private Museums & Educational Groups	240+	752++	345+	38+	59+	23+	121+	74+	25+	88+	188+
Private Collections	283+	436++	176+	75+	78+	8+	257+	124+	145+	188+	127+
Commercial Collections	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
TOTALS:	7,093++	15,275++	1,020+	298+	314+	1,529+	1,359+	509+	218+	1,502+	3,861

Table 9: *The Total Number of Isolated Elements and Teeth By Family of Dinosaur*. The table above shows isolated bones and teeth located in each collection type, during the 2017-2018 Dinosaur Census. Isolated bones and teeth of hadrosaurids, and particular *Edmontosaurus*, were the most commonly identified genera. Unidentified theropod teeth and bones came in with high numbers as well.

unlike many of its northern cousins (e.g. *Monoceratops*, *Einosaurus*, *Pachyrhinoceratops)*, are less frequently found in bone beds of this type (Ryan et al., 2001; Mathews et al., 2009). Only two confirmed bone beds ("Naturalis Quarry" Bastianan and Kaskes, 2016; and "Homer Quarry" Mathews et al., 2009), and one potential site (personal communication Mike Harris, 2011), hold multiple specimen of *Triceratops* (adult to juvenile) and these are not channel lag deposits or crevasse-splays. Another reported, but unconfirmed by database (and not counted) account of a monotaxic Triceratops bone bed includes the AMNH/University of Manchester South Dakota site which mentions the presence of at least 12 individual partial skeletons (Manning and Egerton, 2014). More often than not, however, *Triceratops* is found as isolated skulls or as single specimens in either point bar sandstone deposits or within floodplain mudstones. According to Lyson and Longerich (2011), and personal field observations, they tend to be more associated with flood plain mudstones.

From the database, *Edmontosaurus* isolated bones greatly outnumbered *Triceratops* 46.3%-21.5%. While most of this difference can be attributed to collection bias, the high number of *Edmontosaurus* bone beds and the lower number of *Triceratops* bone beds may have some paleoecological significance. It's possible that *Edmontosaurus* was more gregarious, traveling and migrating in larger herds or that *Triceratops* did not migrate nearly as much. It's also possible that *Edmontosaurus* spent a good deal of its time near these river systems, whereas *Triceratops* preferred to spend more time on the nearby floodplain (Lyson and Longerich, 2011).

Isolated elements and teeth of tyrannosaurids consisted of only 4.6% of the total collection. This is a significant drop from the percentage of associated and/or articulated tyrannosaurid remains (10.9%), again, suggesting various bias in the collection. Of the over 1,300 isolated specimens located, the majority were

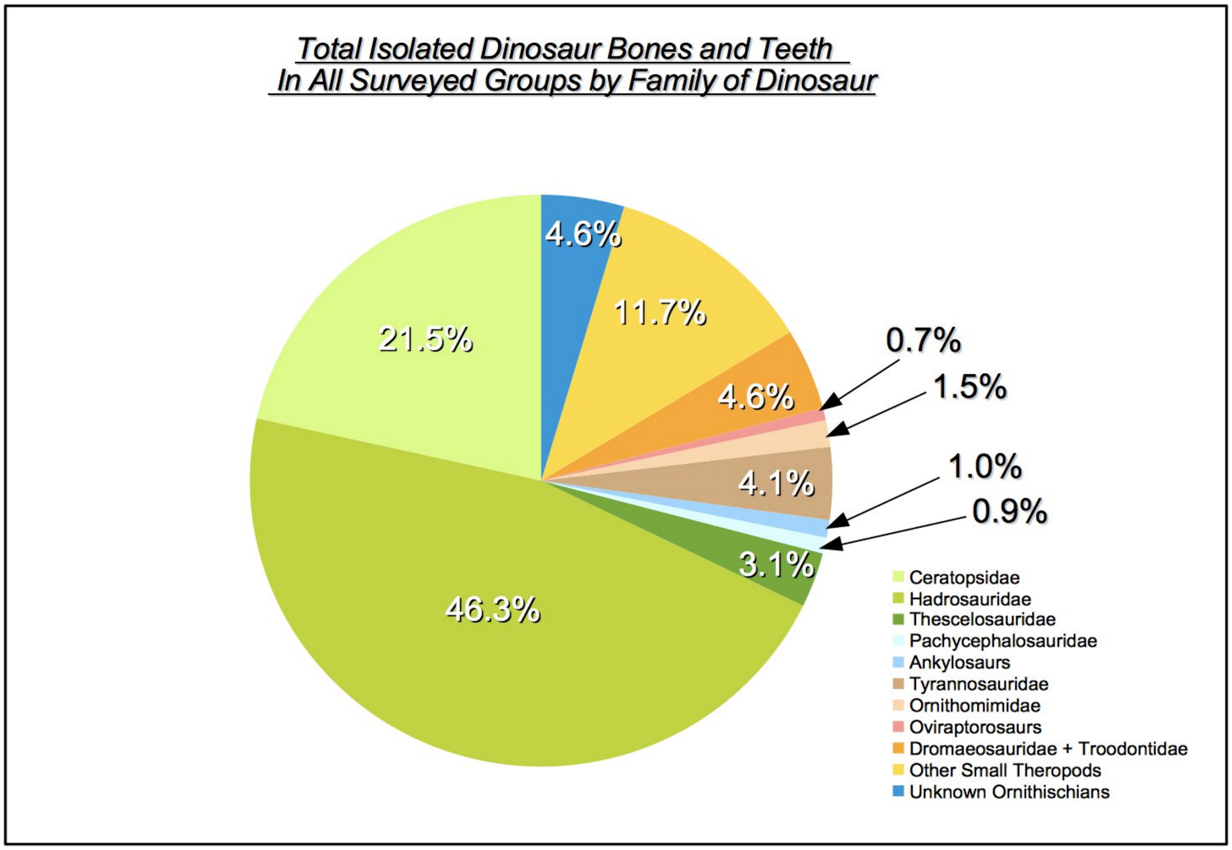

Figure 7: *Isolated Bones and Teeth by Family of Dinosaur.* The graph above shows the relative percentages of isolated bones and teeth for all known taxa in the Hell Creek and Lance Formations. Hadrosaurids were the most commonly discovered taxa, dominating the rest at 46.3%. Ceratopsids drop to second at 21.5%. Small theropods including dromaeosaurids and troodontids came in third with up to 16% of the known isolated elements. The large quantity of specimens and the diversity they suggest, indicates that small theropods were much more common in the ecosystem then previously suggested.

shed teeth. Isolated bones of tyrannosaurids were quite rare in most collections. This suggests a lower overall *Tyrannosaurus* population than previous estimates have implied (Horner et al., 2011).

Isolated elements and teeth from *Thescelosaurus* totaled just over 1,000 known specimens, making up only 3.1% of the total. This shows a similar reduction compared to *Triceratops.* It would seem that when a *Thescelosaurus* specimen is found, it is usually by itself and associated and/or articulated. Isolated bones and teeth tend to be more of a rare occurrence. The only known exception for *Thescelosaurus*, is a single, multi-taxa, channel lag deposit ("Tooth Draw Quarry"- Stein, 2019 in preparation) where dozens of isolated *Thescelosaurus* bones from juvenile to adult, have been found.

Of particular interest is the significant quantity of small theropod (dromaeosaurid + troodontid + unidentified theropod + most likely a few young tyrannosaurid) teeth and isolated bones. These made up over 16% of the total Hell Creek/Lance dinosaur collection. Teeth of the small theropods were quite common, totaling over 5,000 specimens. So, whereas associated and/or articulated material is nearly impossible to find, teeth of genera such as *Acheroraptor*, *Dakotaraptor*, *Saurornitholestes*, *Paronychodon*, *Richardoestesia*, are frequently found. Other genera are commonly found, but they are found in far less numbers. These include cf. Troodon and Pectinodon. While part of this large sample set is certainly a result of taphonomic preservation and collection bias (abundant microfossil screening, surface collecting and "ant hill mining") (Horner et al, 2011; Clemens and Hartman 2002), these very high numbers suggest that small theropods were much more common in the Hell Creek/Lance ecosystem than previously thought.

DISCUSSION:

So, is there enough material to make wholesale judgements regarding the evolution, extinction, ontogeny and faunal diversity at the end of the Cretaceous in the Hell Creek and Lance ecosystems? Based upon the results of my census, the honest answer, for most genera, is "no". Population studies, variation and diversity all require very large data sets for their conclusions to have statistical support. These data sets cannot simply rely on a handful of fragmentary specimens recovered from single sites or regions, but throughout the entire formation and across multiple strata. If we are to make reliable conclusions regarding ontogeny, we need to have dozens of specimens from hatchling to senior, not a handful of fragmentary bits and pieces from juveniles and the rest solidly in the adult category. If we are to make reasonable conclusions regarding extinction or evolution we need multiple specimens correlated with good stratigraphic and geologic context. Not, specimens collected with little to no contextual data, or even dozens of specimens from a single location with limited regional comparisons.

If you intend to make "big picture" conclusions then you need to look at the big picture. One cannot ignore a third of the available material simply because it was privately collected. Or, lump every anomalous specimen or morphologic difference into the ontogenic or individual variation waste bin without recognizing the incredibly small database of associated and/or articulated material we have for review. One cannot fill in the frequent and perfectly normal geologic gaps with outdated, or preconceived assumptions, without first acknowledging the obvious taphonomic issues in fluvially dominated terrestrial rock units. Where there is data, it needs to be used, and where there is statistically insufficient data, the proclamations need to be cautious. With the Hell Creek and Lance, it is best to judge most grand proclamations with caution.

There are certainly enough, mostly complete, specimens of *Triceratops*, *Edmontosaurus*, *Tyrannosaurus*, and *Thescelosaurus* as well as some reasonably complete specimens of *Anzu*, *Struthiomimus*, and *Ankylosaurus* to understand their basic anatomy and evolutionary relationships fairly well. Other specimens are poorly known at this time. Aside from *Edmontosaurus*, most taxa lack data from key ontogenetic stages. This discrepancy ensures some reasonable scientific doubt must be applied to even the most well understood genera. This has direct bearing on any studies of Hell Creek faunal diversity, variation and the timing and mode of their extinction.

Tennant et al., (2018, p. 1), suggested that, "global estimates of faunal diversity are often based on incomplete and distinct regional signals each subject to their own sampling history." They argued that what we think we know regarding faunal diversity is likely to change over time, and largely biased based upon the history of collection efforts in each region. Starrfelt and Liou, (2016, p. 1), acknowledged this as well stating that, "...sampling intensity as influenced by factors such as academic/commercial interest, geographical location and sampling design also influence information from the fossil record we have access to. While some of these factors contribute to noise in our inference of historical patterns and processes, and thus only cloud biological signals, others may cause systematic bias so as to yield misleading results if the data are interpreted at face value or with inappropriate methods." In the Hell Creek and Lance Formation, historical collection bias is quite apparent. Efforts in the Hell Creek and Lance began over 130 years ago, but each period of time brought a new emphasis, and by consequence, a new bias on the collections.

In the late 1800's and early 1900's, the emphasis was on finding, collecting and naming new large-bodied genera and attempting to understand the geologic nature of the rock units. Paleontologists and field workers such as Edward Drinker Cope, Othniel Charles Marsh, John Bell Hatcher, Samuel Williston, Jacob

Wortman, Barnum Brown, Charles Sternberg and others scoured the west, to find and describe new things for YPM, AMNH, USNM, ANSP, KU or CM (Jaff, 2000; Kohl, Martin and Brinkman, 2004; Brinkman 2010). Many of the most important specimens were discovered at this time, but contextual and precise locality information was often not adequately recorded. Due to the methods of the day, the rigors of early fieldwork and the limitations of time, mistakes were certainly made (e.g. damage and loss of skin impressions on the 1884 holotype Tracodon [Edmontosaurus] specimen AMNH 5730, by Wortman, as one example. Osborn, 1912) and duplications of generic nomenclature were frequent. As these rock units were essentially "virgin territory" that had not really been collected, most of these early paleontologists were likely working on the most easily accessible material they discovered weathering out. For example, the majority of the great exposures of Hell Creek Formation in western South Dakota were largely missed by early collectors and not realized until the mid to late 1900's (Stein, 2019 in preparation). I point out these things, not as a criticism of their important work, but as a fact of too few paleontologists with too little time, learning as they went.

By the end of the Great Bone Wars, in the early 1900's, a new period of cooperation began (Kenneth Carpenter, 2018). This was a time of increased sharing of specimens, personnel, and access to research. Many of the errors in duplication began to be worked out. Wealthy industrialists, such as Andrew Carnegie, sought to build the biggest and the best museums. Here, the emphasis quickly shifted to collecting specimens specifically for museum exhibits and displays in an effort to educate the public. Specimens that appeared to be reasonably complete, or in good condition, were highly sought after. The bigger the specimen, the better. In a 1900 letter from the director of the Carnegie Museum, William Jacob Holland, to the curator, John Bell Hatcher, Holland writes: "*It is as you know, of the utmost importance that our museum should succeed in obtaining a fine display of showy things at the outset. Mr. Carnegie has his heart set on dinosaurs-"big things"- as he puts it*." (Brinkman, 2010, p. 129).

Throughout the great depression and the war years, funding for exploration programs was essentially non-existent (Clemens and Hartman, 2014). There were a few trips to the Hell Creek/Lance badlands by museums and universities, but most exploration efforts were shifted to other rock units such as the Dinosaur Park Formation or the Judith River Formation. A few groups continued to dig in the Hell Creek of Montana, but these collections had little "scientific impact" (Clemens and Hartman, 2014). Serious collection efforts in the Hell Creek and Lance had essentially come to a standstill.

By the mid 1950's and throughout the 1960's paleontologists again turned back to the Hell Creek and Lance in an effort to... "bring back a *Triceratops*" or "acquire a *Tyrannosaurus"* for museum exhibits (Clemens and Hartman, 2014; Erickson, 2017, Burnett, 2017). Many of the associated and/or articulated specimens in major museums like the SMM, LACM or UCMP were found by these efforts. By the late 1960's and early 1970's, however, the focus of efforts completely shifted away from big, "trophy" specimens and towards an analysis of the mammalian communities and the microfauna. Microfossil sites were water screened and ant hills sampled in an effort to reconstruct the evolutionary history of the little things under the feet of the dinosaurs. Much of this important work was achieved by bulk processing of matrix through water screening (McKenna et al., 1994; McKenna, 1962; Clemmons, 1973). While there were still a few museums that chased after the large, museum quality, exhibit-worthy pieces, megafauna took a back seat to the microfauna. According to William A Clemmons (former curator of the UCMP) in an interview with Paul Burnett, "*So Harley and others really were contributing more to our knowledge of the large vertebrates of the Late Cretaceous, the dinosaurs, as they sort of—I won't say it, but they [dinosaur skeletons] were weaned away. But no longer was there this real emphasis on filling exhibit halls, which was clearly dominant during the late 1800s and the early 1900s*." (Burnett, 2017, p. 97-98) .

By the 1980's, spurred on by the Alvarez et al. (1980), asteroid extinction theory, and long into the 1990's, collection efforts shifted again, this time to the matter of extinction. Groups turned toward the K-Pg boundary and began sampling the last layers in an effort to determine the rate and timing of the dinosaur's demise. At this time, exploration programs often spent less time collecting specimens and more time surveying and analyzing the context in which the fossils were being found (e.g. Sheehan et al., 1991, Leiggi, 1991). Leaving specimens “in situ” for future studies became the new paradigm (Stein, 2001).

As most field workers know, this concept is flawed. Field identification is often incorrect. It can take weeks or even months of careful preparation and research to properly identify a specimen, and what is eroded out may not truly reflect what is buried underneath. Many specimens that look incomplete, or of poor quality on the surface, might improve dramatically once serious excavation ensues. Horner et al., (2011) discovered this within their own census when re-investigating, formerly uncollected, weathering specimens like *Triceratops*. Once they looked closer at these sites and began serious excavation it became abundantly clear that the remains were often more complete than first realized. Even more importantly, the weather is often not our ally. Over time, an uncollected specimen will become damaged and eventually weather to fragments and dust.

Also during the late 1980's and 1990's many private collectors and large scale commercial groups began to explore the Hell Creek and Lance. These groups were primarily interested in “trophy specimens”, targeting the large, commercially viable megafauna of *Tyrannosaurus*, *Triceratops* and to a far lesser extent, *Edmontosaurus*. Since most American museums at this time were not buying specimens, this led to many specimens being sold to overseas museums (Winters, 2014).

At about the same time, (due to high public interest and an increased number of collectors) channel lag deposits and bone beds began to be excavated by smaller groups, private entities and community colleges. These excavations often led to surprising discoveries that increased our knowledge of the faunal diversity of the Late Cretaceous. This increased interest and competition for sites led to an exponential increase in specimens, but also to some undocumented discoveries and piles of hastily identified material.

Throughout the late 2000's to today, thanks to decreasing budgets and funding (Prothero, 2009), the emphasis has shifted towards more targeted collecting, specifically directed to pre-set, approved and funded research goals (The MOR Hell Creek Project is a notable exception to this). For academia, the emphasis is now less about collecting and more about obtaining a better understanding of the stratigraphy and contextual information at key sites. While this certainly helps to gain important precision in the dataset, it decreases the amount of time spent in broad surveys and thorough site excavation, both of which are necessary to locate the small, rare and delicate genera. All of which takes time, money and manpower. Three things that are becoming increasing short of supply in our modern age.

Not only is it important to look at what was sought after, and ultimately what genera was collected, but also what types of deposits have been explored in depth. Vertebrate fossil accumulations occur in various types. These include: isolated remains, solitary associated and/or articulated specimens, monotaxic bone beds (one taxa dominates), multitaxic bone beds (composed of multiple taxa) and micro-sites (dominated by small vertebrate material). Most associated and/or articulated specimens in the Hell Creek and Lance are found as solitary specimens. Large accumulations of multiple associated and/or articulated specimens found in other rock units like the Morrison, Cedar Mountain Formation, Dinosaur Park Formation, Cloverly Formation and others, simply do not exist in the Hell Creek/Lance. The depositional environments are different. For most of our collecting history, solitary specimens were what was sampled.

Multitaxic bone beds, in crevasse-splays or channel lags where multiple genera are frequently encountered are occasionally found, but seldom excavated in any depth. To my knowledge, only three multi-taxic bone beds have been excavated in any large scale capacity. These include, the “Sandy Site” (TPI/RMDRC/DMNS: Triebold, 1997; Russel and Manabe, 2002; Bartlet, 2004) “Bone Butte” (WPBM/KU- Depalma, 2010) and the “Tooth Draw Quarry” (PARC- Stein, 2019 in progress). Each of these deposits show a time-averaged view of the entire fauna. Generally, these accumulations do not contain associated and/or articulated skeletons, but disarticulated, broken and isolated bones and teeth that have seen a significant level of stream transport or reworking. Occasionally, a partial skeleton is discovered, as with the case of Dakotaraptor (DePalma, 2015) or with Pachycephalosaurus (Triebold, 1997), but these occurrences are rare.

Another depositional issue is that lake deposits are largely absent in the Hell Creek/Lance, and when found are seldom extensive and seldom contain articulated dinosaur taxa (lots of turtle and crocodile, but few dinosaur). In other rock formations, such as the Green River (Grande and Buchheim, 1994), Morrison (Dodson et al., 1980) or Cloverly Formations of the Western United States or the Jehol Group, Xixian and Jiufotang Formations, of China (Zhou, 2006) lake deposits are great sources of fossils, including small-bodied, fully articulated vertebrate taxa (Behrensmeyer and Hook, 1992). The slow accumulation of fine sediment generally helps to preserve small, delicate bones and even soft tissue impressions. Often, these deep lakes are less bioturbated and many have anoxic conditions below a certain depth (Behrensmeyer and Hook, 1992; Martin, 1999). The lack of bioturbation to disturb carcasses and lack of oxygen to prevent rapid decay, helps to preserve smaller bodied organisms. To my knowledge, these types of lake deposits (shallow ephemeral lakes, like the Morrison Fm. or deeper , more extensive lake deposits like those found in the Green River or Xixian), are not seen in the Hell Creek or the Lance.

Ox-bow lake deposits are occasionally found in the Hell Creek and the Lance, and can yield impressive specimens of larger dinosaurs, turtles, crocodiles, champsosaurs, fish and other organisms, but to my knowledge, do not usually produce articulated material like those seen in the rock formations described above. Observed ox bow deposits in the Hell Creek and the Lance are usually shallow, filled with an abundance of organic debris and are often highly bioturbated (DePalma, 2010). This reducing environment, was likely geochemically unsuitable for preserving articulated, delicate vertebrate organisms.

Another factor which may be responsible for the lack of articulated or associated, small dinosaurs, is the suspected high acidity of the Hell Creek and Lance soils (Personal communication Kenneth Carpenter, 2019). According to Carpenter, 1982 (p.123), "*the dominance of drab and somber colored sediments, the abundance of disseminated plant debris and lignite and the presence of pyrite and siderite indicate that the depositional environment was reducing (low Eh). This can be interpreted best as poorly drained, often water-logged soils with numerous marshes or backswamps*". What this means, is that the soil pH was likely quite low, and the formation of sulfuric or carbonic acids acted to decalcify any available small bones and egg shell (Carpenter, 1982). Von Endt and Ortner, (1984 p. 1), in a taphonomic and geochemical study on modern bone concluded that, "*In general, small bones are not as well preserved as large bones, therefore small animals are likely to be underrepresented in faunal assemblages*". Given all of these issues, it is possible that the fluvial and geochemical environment that dominated the Late Cretaceous of this region was just too rough and tumble for most genera under that 400 kg threshold to be preserved. It is therefore, entirely possible that many genera will never be known from more than fragmentary bits and pieces.

Given the history of Hell Creek and Lance collection efforts and its geologic setting, it is not surprising that *Triceratops* is the most common dinosaur discovered. Specimens of such were the first remains found in these units (they did not call these formations the "ceratops beds" without cause) and they are frequently encountered in the field today. *Triceratops* skulls and skeletons are easily seen during exploration. If a specimen has been weathering for some time, it usually leaves a large and unmistakable float trail that can be seen from many meters away. *Triceratops* was, simply put, a massive animal. It had a massive skull that in most adult specimens, exceeded over two meters in length. It was heavily ossified and resistant to weathering and erosion. Based upon its high census numbers, they were most likely quite common in the Hell Creek ecosystem and the dominant low browser of its day (see Ostrom, 1964 for description of dentition and diet). It is no wonder why the vast majority of associated and/or articulated specimens recovered from these beds are *Triceratops*.

It is also no surprise that associated and/or articulated specimens of tyrannosaurids produced such high numbers. Tyrannosaur skulls and skeletons made up nearly 11% of the total collection. Like *Triceratops*, they were large animals. Adult *Tyrannosaurus* specimens frequently exceeded 10 meters in length or longer and could weigh 7,000 to 9,000 kg. Just like *Triceratops*, their bones are more resistant to weathering. Even though many tyrannosaurid elements are hollow, these often have dense, thick, cortical layers that are resistant to weathering. Once broken and eroded they often have a jagged, glassy look that is unmistakeable and easily seen from some distance. It is hard to miss a weathering *Tyrannosaurus* if it has been exposed for some time. More importantly, they have been highly sought after since their initial discovery, description and exhibition. In the 1990's, after the discovery and subsequent controversy over the "Sue" *Tyrannosaurus* specimen, and its auction for over 8.3 million dollars, collectors flocked to the Dakotas in an effort to find more. Museums all around the world wanted one. Given the large number of people hunting for *Tyrannosaurus*, its size and preservation potential, it's not surprising that many were found.

Horner et al, 2011, suggested that the high number of associated and/or articulated specimens of *Tyrannosaurus* in their census, was not simply a matter of collection or preservational bias, but an actual artifact of dinosaur populations in the Late Cretaceous. They suggested/implied that *Tyrannosaurus* may have totaled up to 24% of the large megafaunal population and concluded from this that *Tyrannosaurus* had to acquire much of its food via scavenging. All of this is highly unlikely. No modern megafaunal assemblage could sustain the presence of this many top-tier, large carnivores. For example, according the the IUCN Redlist website, the total estimated population of mature African lions today is roughly 23,000-39,000 individuals (Bauer et al., 2016). Their main prey species include wildebeest (1.5 million), zebras (660,000), pigs (250,000), Cape buffalo (890,000) giraffes (68,000) gazelle (550,000) and multiple species of antelope (6-7 million). Combining their main prey's estimated populations there are at least 9 million potential individual prey items. This, of course, does not take into consideration variations in geographic range, smaller prey items that they will occasionally take or smaller predators they would be competing with, but, at the top end of their numbers, lions, as a percentage of this population would be only 0.4%. This is, of course, only one, very simplified example, but I think the point is clear. The most parsimonious answer is that this increased number of Tyrannosaurid specimens is a direct result of taphonomic and collecting bias. Given that isolated bones and teeth of Tyrannosaurids made up less than 5% of the collection and partial skeletons were only 11% of the total collection (with clear bias), the actual population of *Tyrannosaurus* in the Hell Creek/Lance ecosystem was, more than likely, closer to 5%, than 24%.

The duck-billed hadrosaurids are also well represented in the Hell Creek/Lance collection record, thanks to their large adult size and their apparent preference for this lowland floodplain environment. What is surprising may not be the high number of specimens, but rather that it wasn't higher. I am aware of several instances where hadrosaurids were not collected, simply because they were hadrosaurids. Actual percentages should most likely have been higher, had collection bias not selected against them. The other surprising issue regarding hadrosaurids is their apparent lack of diversity when compared to other Cretaceous rock formations (e.g. Dinosaur Provincial Park Formation, Brown et al., 2012). The overwhelming majority of specimens were identified as *Edmontosaurus* and most authors argue that it is the only genera present (Horner et al., 2004; Campione and Evans, 2011). While some authors have suggested the presence of *Anatotitan* (Brett-Surman, 1985), and there have been rare references to and unidentified crested hadrosaur (Boyd and Ott, 2002), the absence of a large quantity of lambeosaurine specimens suggests hadrosaurid diversity may have been on the decline in the Late Cretaceous of North America (Barrett et al., 2009; Campione and Evans, 2011; Upchurch et al., 2011; Brusatte, et al., 2014).

This begs another question: Why are *Triceratops*, *Edmontosaurus* and *Tyrannosaurus* skeletons and skulls so common and *Ankylosaurus* and *Denversaurus* skeletons and skulls so rare? *Ankylosaurus* and *Denversaurus* were both extra-large bodied dinosaurs, over 2,000 kg, with stout, heavy bones. These should have preserved just as well as ceratopsids, hadrosaurids and tyrannosaurids. They are certainly just as sought after. Does this mean that ankylosaurids were simply more rare in the Hell Creek ecosystem or is there some taphonomic reason for their lack of preservation? I am aware of at least two cases where ankylosaur material was found as only large collections of scutes, devoid of nearly every post cranial element. One specimen in particular, was collected from the Lance in 2011 by myself and the land owner (Harris collection). The other was collected sometime in the 1980's, by teams from the South Dakota School of Mines and Technology (Finlayson, 1997). Hundreds of scutes were found in both cases, but only a few skeletal bones. Both of these were discovered in what appeared to be oxbow lake deposits with an abundance of plant remains. These specimens suggest something unusual regarding the preferential preservation of the armor vs. the skeletal elements. While ankylosaurids may have been a much rarer sight in the Hell Creek and Lance ecosystem, the evidence, points to a taphonomic cause rather than a collection bias or a faunal diversity issue.

Other than *Thescelosaurus* which has a substantial associated and/or articulated dataset, smaller herbivores and omnivores, are also less commonly found. These include the pachycephalosaurs, young hadrosaurids and other suspected ornithischians. Hone and Rauhut (2009), rightly pointed out that the lack of associated and/or articulated specimens of small to mid-sized herbivores may be associated with preferential hunting or scavenging by larger theropods like *T. rex*. Shed *Tyrannosaurus* and *Nanotyrannus* teeth are a common sight at many *Edmontosaurus* specimens. It is likely that the lack of material is directly related to both scavenging activity and rapid weathering of smaller, less ossified, elements, along with a collection bias towards larger specimens. Just about anything under 400 kg (other than *Thescelosaurus*) falls into this category.

Small theropods are also largely absent from the associated and/or articulated dataset Unlike the extra-large bodied *Tyrannosaurus,* theropods under 400 kg like *Dakotaraptor*, *Acheroraptor*, *Anzu*, *Struthiomimus*, c.f. *Troodon*, etc. had elements that were exceptionally lightweight and extraordinarily fragile. Bones of these animals are hollow with cortical bone, often as thin as eggshells. Isolated bones of these animals, weather quickly in modern badland environments. Often, isolated remains are only discovered upon very close inspection of rocky surfaces. Float trails from these fragile elements usually consist of short runs of multiple paper-thin fragments that are often easily confused with modern plant detritus (sticks, twigs, leaves), fossil plant fragments (petrified wood) or bits of secondary minerals (thin rinds of gypsum, calcium carbonate or ironstone). Is it any wonder that young tyrannosaurids, dromaeosaurids, ornithomimids, oviraptorosaurids, troodontids and alvarezsaurids are so incredibly rare in the fossil record when compared to the large bodied and heavily built *Triceratops*, *Edmontosaurus* or adult *Tyrannosaurus?* Based on isolated remains, both small ornithischians and small theropods were most likely a large component of the population. Animals under 400 kg (other than perhaps *Thescelosaurus*), simply did not preserve very well or as often in the chaotic and fluvially dominant Hell Creek and Lance ecosystems.

CONCLUSION:

The faunal diversity of the Late Cretaceous Hell Creek and Lance ecosystems, based upon the total collection of both associated and/or articulated skeletons/skulls and isolated bones and teeth, appears to be just as vibrant and healthy as those found in many other North American Cretaceous rock units, with some exceptions (Brusatte, etal., 2014). The difference between the Hell Creek/Lance and earlier rock units appears to be largely related to both taphonomic and collection bias. It is clear from the combined available data set that these biases are major factors in how we currently view the dinosaurs of the Hell Creek and Lance ecosystems. For extra-large bodied organisms like *Triceratops*, *Edmontosaurus* and *Tyrannosaurus*, we have a large, sufficient number of mostly complete, well preserved, adult and sub-adult specimens, but remarkably few younger individuals. We have a reasonably complete dataset of some large bodied taxa like *Thescelosaurus* and a handful of partial to complete skeletons of *Struthiomimus sp.* and *Anzu*. The ankylosaurs are known from just a few good skulls and skeletons, but typically are represented by associated scutes. Pachycephalosaurs are known predominately from isolated fronto-pareital domes and the occasional partial skull with little post-cranial material.

Unfortunately, after 130+ years of intense exploration, we really have very little data on everything else. Isolated bones and teeth suggest a healthy diversity, but taphonomic preservation and a bias towards extra-large-bodied taxa over 2,000 kg have skewed our perception of this wonderful ecosystem. I have no doubt, that as the years progress, additional, well preserved specimens will be discovered which will help clarify the ambiguities and fill in the holes. Its only a matter of time before the next “new” genera or species decides to reveal itself.

The only way to achieve such a large dataset, however, is to keep collecting. The more groups exploring and excavating and documenting, the greater the chance there is to fill in those missing gaps. When a new piece of that puzzle is discovered, collectors need to share that information as quickly as possible and distribute it to all interested parties, via open-source research papers and documented through online databases. This goes for academics, avocationalists and commercial groups. As stated before, online collection databases are a great way to share information with other researchers. This increases public/professional scrutiny, improves collections, helps identify and eliminate bias, and can help foster new collaboration efforts. Every museum, institution, university, non-profit and large-scale collector should have or be moving towards, an openly available, online presence.

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