Angus Genetics Inc. Imagine Forum White Paper:

Exploring Next-Generation Phenotyping that Drives Commercial Profitability

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"In the age of genotype, phenotype is king!" – Prof. Mike Coffey (Scotland's Rural College)

Genetic evaluation, the process of calculating expected progeny differences (EPDs) for economically relevant traits (ERT), has driven enormous genetic improvement in the beef industry. From their inception in the 1970s, genetic evaluations have relied on the widespread collection and aggregation of phenotypes, typically by breed associations [1]. These phenotypes are captured from birth (calving ease or birth weight) to post-harvest (marbling or carcass weight) and every point between. Recent innovations in genomics and modeling approaches have increased the accuracy of genetic selection tools and driven improvements across the industry[2]. Despite these innovations in genotyping and modeling, continued phenotypic collection remains as critical as ever.

As the beef industry changes and methods for capturing phenotypes on previously unmeasurable traits emerge, innovations in phenotyping will be essential to driving sustained change in our cattle populations. Even for traits with reliable genetic evaluations (e.g., weaning weight, calving ease), if phenotyping were to abruptly stop, predictions would rapidly lose efficacy. While continued innovations in statistical methods and genotyping may enhance prediction accuracies in the future, the most important developments will stem from the introduction of new, economically important, but hard-to-measure traits in our genetic evaluations.

Beyond measuring novel phenotypes, genetic evaluations will also need to find innovative ways to capture data from commercial sources. Data from commercial herds can bolster the total number of phenotypes for some rarely measured traits (e.g., carcass, health, or reproduction), as well as provide performance benchmarks in the environment and management contexts where seedstock genetics are being utilized. The addition of commercial phenotypes, particularly when paired with verified sires and/or genomics, could rapidly build on the industry's expansive phenotypic catalog.

These themes and others were all explored at the first-ever Imagine: AGI's Beef Genetics Forum hosted by Angus Genetics Inc. (AGI®) in Kansas City, MO, on September 25-26, 2024. This event brought together leaders from across producer, industry, and academic segments of the industry to imagine how innovative phenotyping strategies could help increase the sustainability and profitability of beef production. The forum explored a diverse set of emerging technologies and brainstormed the areas of greatest need and highest potential. In addition, they received historical context from breeders and perspectives from members of other industries. This whitepaper explores some of the major themes identified by the group and provides considerations for paths forward.

A Brief History of Phenotyping and Genetic Evaluation at the American Angus Association®/AGI®

Brian McCulloh of Woodhill Farms, an Angus breeder, opened the forum's conversation by walking through the American Angus Association's history of genetic evaluation. In 1956, breeders came together and identified a need for performance recording across the breed. This was, in effect, the first effort at the Association to intentionally collect and aggregate phenotypes (i.e., weights). The introduction of open artificial insemination in the registry in 1972 presented a need and sufficient data for the calculation of expected progeny differences (EPDs) in the early 1980s[3]. This led to expanded phenotype collection efforts and the creation of EPDs for phenotypes across industry segments.

To provide commercial producers with easier-to-interpret tools that were profit-centric, Angus released the first of its selection indexes in 2003; $F, $G, and $B focused on the trait complexes that increased profitability in the feedlot, on a carcass grid, and across the full terminal retained ownership scenario.

The last two decades have been marked by innovations that integrated genomics into genetic predictions, resulting in increased EPD accuracy and more rapid genetic progress[1–5]. In addition to these advances, the Angus evaluation has added new traits related to health, welfare, and adaptation traits, each of which have economic importance to commercial herds. This includes the release of foot conformation traits (CLAW & ANGLE) in 2020, pulmonary arterial pressure (PAP) in 2021, and hair shedding (HS) in 2022. The breed's most recent efforts include traits focused on maternal function with the release of functional longevity (FL), teat size (TEAT), and udder suspension (UDDR) research EPDs in late 2023 and 2024.

Gaps in phenotyping still exist, as many ERTs may go unaccounted for in genetic evaluations because we lack straightforward and cost-effective methods for measuring indicators[6]. Phenotypes that are easily captured, such as for our growth traits, are already well-represented in evaluations. Others, like feed efficiency or carcass ultrasound, have high overhead collection costs that are shouldered by seedstock producers. This results in substantially lower numbers of records. Traits such as disease tolerance, forage-based feed intake, and enteric methane emission present unique challenges to collection.

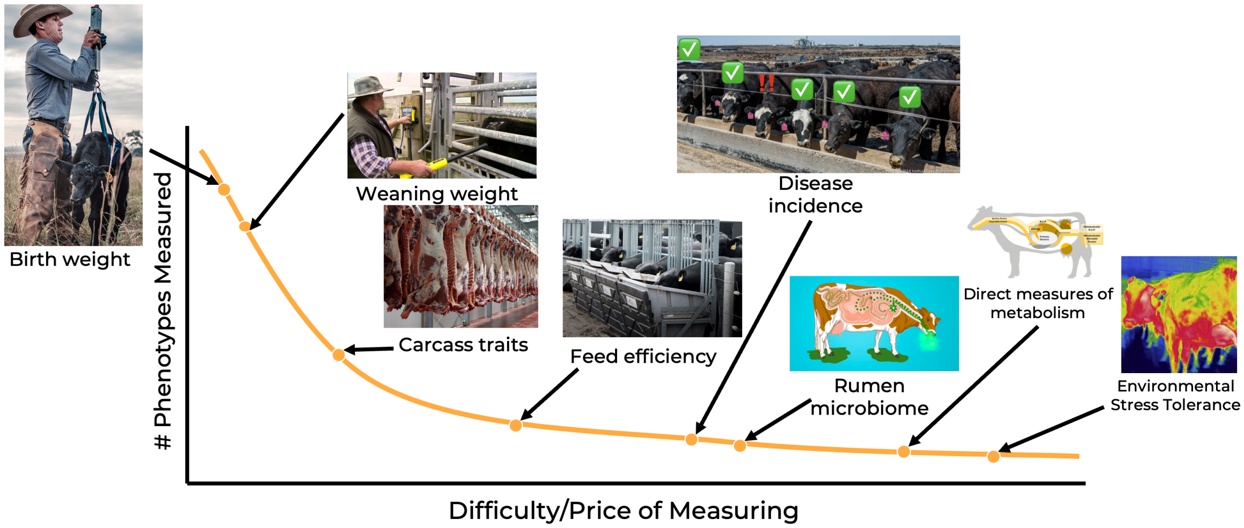

Figure 1. "The Phenotyping Paradox" – A hypothetical relationship between the difficulty or price of measuring a phenotype and the likely number that we can capture.

Opportunities for Collecting Novel Phenotypes

Computer Vision

Innovations in artificial intelligence present opportunities to leverage imaging to extract a wide range of informative phenotypes from the routine monitoring of cattle. These range from passive collection of weights and body condition scores to more precise estimates of red meat yield in carcasses. Dr. Guilherme Rosa's presentation underlined the value of computer vision in the phenotyping space well: "An image is worth a thousand measurements." This thought underlines both the value of imaging approaches to phenotyping as well as the challenges presented as we attempt to make sense of these high-dimensional data sets.

One major benefit to using computer vision approaches for phenotyping is that operations may be able to capture and report phenotypes passively and repeatedly. Further, the value of imaging systems is enhanced because they are likely to provide real-time insights to producers interested in making management decisions. One such system that is being actively implemented is called OneCupAI. Its creator, Mokah Shmigelsky, described how a system designed primarily for management monitoring has turned into a powerful phenotyping tool. This system uses strategically placed cameras to develop a system that uniquely identifies animals and categorizes a wide variety of behaviors and phenotypes. This includes things like calving, estrus, lameness, and illness. Emerging collaborations with breed associations in Canada are testing integrated modules that focus on the passive, longitudinal collection of phenotypes into this ecosystem.

Presentations at the forum highlighted a variety of cases of computer imaging being used in management and phenotyping applications. Dr. Guilherme Rosa (University of Wisconsin-

Madison) detailed his lab's work on using imaging systems for phenotyping across beef cattle, dairy cattle, swine, and poultry[7–9]. These applications all blended decision support tools with high-throughput phenotype collection. Further, Rosa's presentation emphasized the potential for using imaging-based solutions in phenotyping unlocks new opportunities to understand and select for temporal phenotypes (e.g., shifting growth curves) or body composition (e.g., lengthening primal cuts)[10]. Ultimately, these technologies offer opportunities to measure phenotypes more precisely, breaking out of the categorical nature that we often impose on actually continuous traits (e.g., foot scores, hair shedding scores, body condition scores)[11]. This increased precision of measurement should, in theory, increase the accuracy of EPDs calculated based on these phenotypes.

One other area of phenotyping that will benefit significantly from innovations in the computer vision space is carcass evaluation. Dr. Dale Woerner (Texas Tech University) led a discussion on the evolution of evaluating red meat yield in the beef industry[12]. Woerner and the Red Meat Yield Task Force's work shows there is a major discrepancy between the present yield grade formula and actual red meat yield. External body conformation and muscling phenotypes are currently not captured as phenotypes in genetic evaluations but have a major impact on cutout weights. New developments in 3D imaging and CT scanners present opportunities to collect extremely detailed phenotypes on carcass composition, quality, and yield[13]. Woerner emphasized that genetic evaluations would benefit enormously from receiving real phenotypes back from packing plants. As with on-farm imaging solutions, the automated collection of these phenotypes in packing plants could have enormous impacts on genetic evaluations while more precisely compensating producers for end product.

Health Traits and the Microbiome

The forum's program also highlighted two major emerging areas of interest to the beef industry: immune phenotyping and the role the rumen microbiome plays on traits.

Diseases cause enormous economic losses throughout segments of the beef industry[14]. Immune resistance and resilience phenotypes are under natural selection to a degree, but generally, our management interventions have been the only viable strategy for increasing herd health[15]. Major challenges exist in capturing informative and repeatable disease phenotypes as disease complexes (e.g., Bovine Respiratory Disease) can be driven by largely different sets of pathogens and environmental factors. Further, sub-clinical disease, which we know has appreciable effects on animal performance, is next-to-impossible to quantify in production settings [16].

Dr. Larry Kuehn discussed opportunities to address both pathogen resistance (reducing shedding/infectivity through herd) and resilience (adapting to pathogen/environmental stressors) as avenues for genetic improvement. To circumvent challenges in defining disease, Kuehn described the importance of objectively measured indicator phenotypes. The dairy industry has benefitted enormously from somatic cell count phenotypes in genetically addressing mastitis[17]. Other phenotyping approaches in the dairy industry take advantage of regular milk samples to produce useful proxy phenotypes for traits that are difficult to measure (e.g., feed efficiency, methane emission, ketosis, etc.)[18]. Developing tools to address disease resistance and robustness in the beef industry will require similar types of outside-the-box thinking. Approaches may include measuring disease-related organs (e.g., heart, lung, liver) in terminal animals with a standard scoring system[19]. Other methods that measure responses to vaccines or other immune stimuli may make for more useful phenotypes[20]. Objective visual scoring methodologies driven by innovations in computer vision may also help to pave the way for more consistent disease event recording[21]. Beyond phenotyping challenges, selection for disease resistance may require a unique approach to breeding due to the importance of maintaining diversity at certain immune loci[22].

Ruminants rely on the microorganisms that colonize their rumens to extract energy from low-quality feedstuffs. Dr. Jefferson Laurenco (University of Georgia) described his group's work on characterizing the microbiome on large groups of animals. They have identified numerous areas where the microbiome might be of interest to genetic evaluation, from helping to refine and model environmental and diet differences to serving as indicator traits for hard-to-measure phenotypes. It is also clear some elements of the rumen microbiome are under host genetic control, meaning that direct selection for certain microbial populations could accelerate genetic progress for traits like feed efficiency or methane emission[23].

Developing Technologies: In Summary

New phenotyping approaches are developing rapidly in the beef industry, from computer vision to wearable sensors and immune phenotyping to understanding the microbiome. These technologies offer exciting opportunities to capture information never previously accessible to genetic evaluations. Phenotypes measured more precisely and uniformly will result in more accurate downstream selection tools. However, the largest benefit to many of these systems may be their ability to automate reporting, lowering the barriers for producers to collect phenotypes. Actively implementing these systems will require a clear understanding of the return on investment for producers and a reimagining of how genetic evaluations serve as "phenotype processors" in the future.

Attendees saw examples and strategies for development and applications of these systems in the pork breeding industry, with insights from Dr. Bradley Wolter (formerly Maschofs) and Dr. Marcos Lopes (Topigs Norsvin). For deployment in the beef industry, new resources and infrastructure will be needed, and producers will have to place even more confidence in their genetic evaluations to oversee phenotypic processing. Beyond seedstock breeders, these novel strategies may further encourage the collection of phenotypes from commercial herds.

Phenotyping Strategies and Investments

A Focus on Commercial Profitability

Since the inception of genetic evaluations, breed associations have been a logical home for phenotypic data aggregation and EPD calculation in the beef industry for both breeding program (seedstock operations act as genetic nuclei for the wider industry) and logistical reasons (they were already managing pedigrees). This setup has worked well historically, resulting in unprecedented genetic progress for a range of ERTs[24]. That said, segmentation across the industry introduces the risk of suboptimization in breeding decisions at the commercial level, where focusing on certain traits for one segment may make the full system less efficient. Future phenotyping initiatives in the beef industry should ensure that capturing data from and for the commercial herd is a cornerstone attribute. This must include collecting relevant data across segments (cow-calf, backgrounding, feedlot, processing, consumer experience) and across a diverse range of environments.

The ideal genetic evaluation for the beef industry must be centered on improving the full suite of traits that drive commercial profitability. This requires genetic evaluations that consider all profit drivers, both revenues and costs. Recent genetic selection for traits related to end-product yield and quality traits (i.e., revenue) has been an overwhelming success for the industry. Revenue-generating traits will continue to be essential pieces of the industry's breeding objective. However, increased attention on traits that contribute to to an enterprise's costs, specifically related to heifer development, cow maintenance, and overall fitness of the population will require an increased share of our attention to drive continued profitability increases. Further, supply chains that develop around sustainable, antibiotic-free, or welfare-centric beef may require that we evaluate new sets of traits as profit drivers.

Phenotyping bottlenecks at both the seedstock and commercial levels are the major reason why many important profit drivers are absent from current genetic evaluations. Expanded phenotypes for these traits would serve two main purposes. First, they could help us predict genetic merit for traits completely missing from current evaluations (e.g., disease resistance). Second, they could help us more precisely measure ERTs that are currently captured by imperfect indicators (e.g., forage intake vs. its indicator, mature weight).

Collecting phenotypes and developing selection tools are only part of a larger challenge. Quantifying the economics of these cost-related traits is essential for integrating these traits into selection index tools for commercial herds. Deriving the economic impact traits like fertility, structural soundness, docility, or udder quality, are exceedingly complex. These traits all have varying effects on cow longevity, calf productivity, and labor inputs. They may also change with the severity of the phenotype or shift non-linearly over the course of an animal's lifetime. For example, a poor quarter of an udder may start as a relatively small driver of decreased performance, then require labor inputs in getting a calf to begin nursing, and ultimately lead to an early-life culling decision. This makes these traits incredibly difficult to economically model. Long-term research quantifying their economic value will be essential for appropriately weighting them in indexes.

Strategic and Optimized Phenotyping Efforts

Understanding the economic importance of these traits also shapes phenotyping strategy. Just because we can measure something does not make it an ideal candidate for widespread phenotyping. Expensive or hard-to-collect phenotypes that already have an adequate indicator may not generate sufficient improvements in selection response to justify the cost of measurement versus the value to the genetic evaluation. It is essential we understand the return on investment, both financially and in the genetic evaluation of novel phenotyping approaches.

We can classify traits and their indicator phenotypes using two main factors and then divide them into four groups that dictate how we might undertake phenotyping. Traits can be defined based on their value and difficulty of measurement. This results in four distinct classes that help prioritize phenotyping efforts.

1) Traits with high economic values that are easy to capture should be immediate priorities for phenotyping. These are the quintessential low-hanging fruit. In many cases, these can be undertaken exclusively by producers, and the selection tool generated by their collection is a sufficient incentive for data collection. Novel traits like hair shedding and foot score phenotypes fall into this category.
2) Traits with high economic values but that are more difficult to collect present a unique challenge. Their importance to the breeding objective is clear, but producer collection may be impossible or may present an expense that is unable to be fully captured by the value of the resulting selection tool. This is particularly true for cases where multiple segments of the industry capture value from the trait. Enteric methane emission phenotypes would fit squarely into this category. Current methods for collection are expensive and difficult. Additionally, the economic importance is becoming increasingly apparent, though which segments of the industry capture value for reductions is much less clear. Ultrasound carcass data falls into this class of traits, as a small set of seedstock operations bear the majority of costs, while the rest of the industry benefits from selection tools generated by these individuals.
3) Traits of low economic importance that are easy to collect are unlikelty to return value to an evaluation. When included, these traits with minimal economic value create more work in data collection and aggregation while potentially taking up a portion of the breeding objective that should be allocated to more economically-important traits.
4) Traits that have low economic importance and are difficult and expensive to collect are best ignored by genetic evaluations.

Phenotyping strategy should focus its attention on traits that fit into the first two of these classes. The industry should search for any opportunity to capture easy-to-collect, high-impact phenotypes. These are ideal candidate traits to capture from commercial herds. It is also important to remember the difficulty and cost of collection may shift over time as technologies become more easily accessible. This is discussed in-depth in the following section, but passive monitoring technologies like computer vision systems or wearable sensors may be purchased for management reasons and generate useful phenotypes as byproducts.

We may also need to consider what targeted phenotyping initiatives look like. Aggregating voluntarily reported data will continue to be an important component of genetic evaluations. However, targeted phenotyping herds that maximize genetic connections to the larger population could help maximize the return on phenotyping investment[25]. While not explicitly a progeny test, these targeted phenotyping herds would be central to the rapid development of EPDs for novel traits. These targeted phenotyping herds could also allow other industry actors to help shoulder some of the financial costs of phenotyping that they would ultimately benefit from.

Capturing Commercial Data

Commercial phenotypes have enormous potential in the next generation of genetic evaluations. Measuring phenotypes in commercial environments may help refine the role of genetics-by-environment interactions that limit the portability of EPDs between seedstock and commercial herds. This will be particularly important for traits like fertility, where breeding programs may look starkly different between seedstock herds – where artificial insemination and embryo transfer are used extensively – and commercial herds which may almost exclusively use natural service. Health and immune traits may benefit even more from phenotypes collected in less intensively managed commercial herds. Even routinely collected phenotypes from commercial herds may benefit genetic evaluations.

Despite its clear value to genetic evaluations, commercial data recording remains limited. The labor and time commercial producers devote to phenotypic collection and reporting must be matched with valuable management tools on the other side. In the immediate term, commercial herd management software that records basic cow inventories and calving records could be a useful starting point for genetic evaluations interested in integrating commercial data for cow-related performance and fertility traits.

Historically, seedstock producers have shouldered the cost of phenotyping, where the value proposition relates to improving the availability and accuracy of selection tools. The collection of expensive, high-impact phenotypes in commercial and seedstock herds will require collaboration between seedstock breeders, commercial herds, breed associations, and operators across the industry. Beyond potentially sharing in the costs of phenotype collection, this coordination will help with ensuring that individual animal data is traceable and portable between actors, as well the development of harmonized data collection systems and trait definitions. In cases where commercial data is shared across industry segments, establishing clear frameworks for data ownership will be central to the long-term success of these initiatives.

Wide-scale phenotyping initiatives may not be practical for all traits, even in seedstock populations. In some cases, passive monitoring systems could allow for the automated collection of phenotypes while these systems provide greater value in monitoring and decision support for management interventions. One potential example might be using a computer imaging system designed for routine herd surveillance to passively capture repeated records for body condition scores, structural attributes, hair shedding, and other visually observed traits. Another might be using an ear tag-based accelerometer to estimate feed intake for grazing cows or to precisely catalog natural service breeding events. These phenotypes, along with their precise metadata, could then be forwarded to breed associations without a producer ever having to record or send data.

Integrating any commercial data into genetic evaluations will be entirely reliant on widespread commercial genomic testing[6] to provide ties to the seedstock population. Without this clear link, these phenotypes will fail to provide any value. Innovations in genomic sequencing and genotype imputation[27] will continue to reduce genotyping costs, making commercial genotyping significantly cheaper.

A Path Forward

The innovations presented at Imagine: AGI's Beef Genetics Forum will undoubtedly find their way into phenotyping efforts in the future, and opportunities exist to drive some of these changes in the immediate term. The greatest opportunities moving forward rely on capturing and leveraging commercial data throughout the value chain. This will require radical collaboration and coordination between industry partners. While individual data points from a commercial herd or a processing plant may not be individually valuable, capturing multiple sources of data in the aggregate will enable genetic evaluations to fill important gaps in their systems with high-quality tools.

These efforts that leverage new technologies and integrate new data sources will require five main considerations:

1) **Phenotypes are, and will always be, the backbones of genetic evaluation**: While much of our forward-looking focus is on new and novel phenotypes measured by increasingly complex technologies, we still have far from complete reporting for our core ERTs. No amount of genomic testing can make up for a lack of phenotypic reporting. In the immediate term, the continued adoption of whole herd reporting (i.e., inventory-based reporting) will improve genetic predictions and open opportunities to extract new phenotypes (e.g., calving interval, etc.).
2) **Standardization of phenotype collection, both by producers and via algorithms, will be essential**: From the inception of genetic evaluations, we have worked to standardize trait definitions and best practices for recording. This motivated the creation of the Beef Improvement Federation, which continues to publish best practices. Next-generation phenotyping technologies will have many more variables that can impact raw phenotypes, making the standardization of recording, processing, and cleaning even more important. Consistent trait definitions will be essential for ensuring that regardless of platform, phenotypes can flow in and be analyzed together. This will be equally true for the integration of commercial

phenotypes. To maximize utility and minimize barriers to participation, genetic evaluations and hardware/software providers will need to work together to standardize data reporting.

3) **Seedstock producers may not be able to shoulder the full financial burden of phenotypic collection**: Seedstock producers have traditionally borne the full cost of phenotyping with the understanding that records will help increase the accuracy of EPDs for their animals. However, as we seek to measure more expensive phenotypes, the economics of phenotyping will become more difficult. Capturing phenotypes for traits like methane emission or feed intake carries substantial costs, and in many cases, the seedstock producers and their customers (cow-calf producers) capture only a fraction of the value of genetic progress. Upstream actors interested in improving these sustainability-related traits may need to invest in targeted phenotyping efforts for the improved genetics that they ultimately profit from.
4) **Genetic evaluations will have to balance the deluge of new technology with the resulting payoff in EPD quality and utility**: Not every phenotype is worth measuring. As new technologies come online, genetic evaluations will need to consider the costs and return on investment carefully. Expensive-to-measure traits that contribute minimally to breeding objectives would likely fail to generate sufficient value. Beyond the costs of recording, the time and effort spent on troubleshooting and deploying a new trait in the evaluation is considerable. Before widespread phenotyping occurs, evaluations should carefully consider these economics. It is also important that these evaluations are not short-sighted or reactionary.
5) **Data sharing will be essential to leveraging the impact of phenotypic collection across industry segments**: Economically important phenotypes can be collected at every step of the beef supply chain. From cow-calf operations to feedlots to processors to consumer feedback, data is constantly being collected. When we can tie this data back to an individual animal and its genetics, the possibilities of improving efficiency, animal well-being, and consumer experience are limitless. To make this a possibility, it will require unprecedented data sharing and cooperation. This all starts with individual animal traceability and standardized recording schemes. Each entity understands the value of their data, so genetic evaluations must find ways to demonstrate how their access to the data will benefit upstream actors or find strategies for anonymization.

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