Digestion of Grass Forages and Their Utilization in Dairy Rations

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and

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Introduction

- Cows evolved to digest the complex carbohydrates in grass cell walls (fiber)
  - Cows are grazers not browsers
- Fibrous carbohydrates digest slowly and need long retention times for digestion
  - Can only be digested by microbial enzymes
- Reticulo-rumen (fermentation chamber) is the largest compartment of the ruminant's stomach
  - Warm, liquid, buffered environment with feed provided and end-products removed by the cow
  - Symbiotic growth of ruminal microorganisms that fermentatively digest fiber and provide VFA and microbial cell protein to the animal

Introduction

- Ruminal environment is mutually beneficial (symbiotic) to microbe and animal, but not perfect
  - Anaerobic (oxygen limited)
  - Carbohydrates (CHO) cannot be fermented to CO_2 and H_2O
    - $CHO + O_2 \rightarrow CO_2 + H_2O$
  - Anaerobic fermentation:
    - $CHO \rightarrow CO_2 + CH_3 + VFA$

Introduction

- Kinetics of digestion and passage are keys to grass digestion
  - Fiber often exceeds 50% of grass DM
  - Fiber digestion is slow
    - To achieve 95% digestion requires 24 to 72 h
  - Adverse ruminal conditions (low pH) and negative interactions with other feeds can slow digestion further
    - Can add 8 to 24 hr to digestion time
  - Rate of passage of lactating cows is high
    - From retention time of 50+ to <30 h

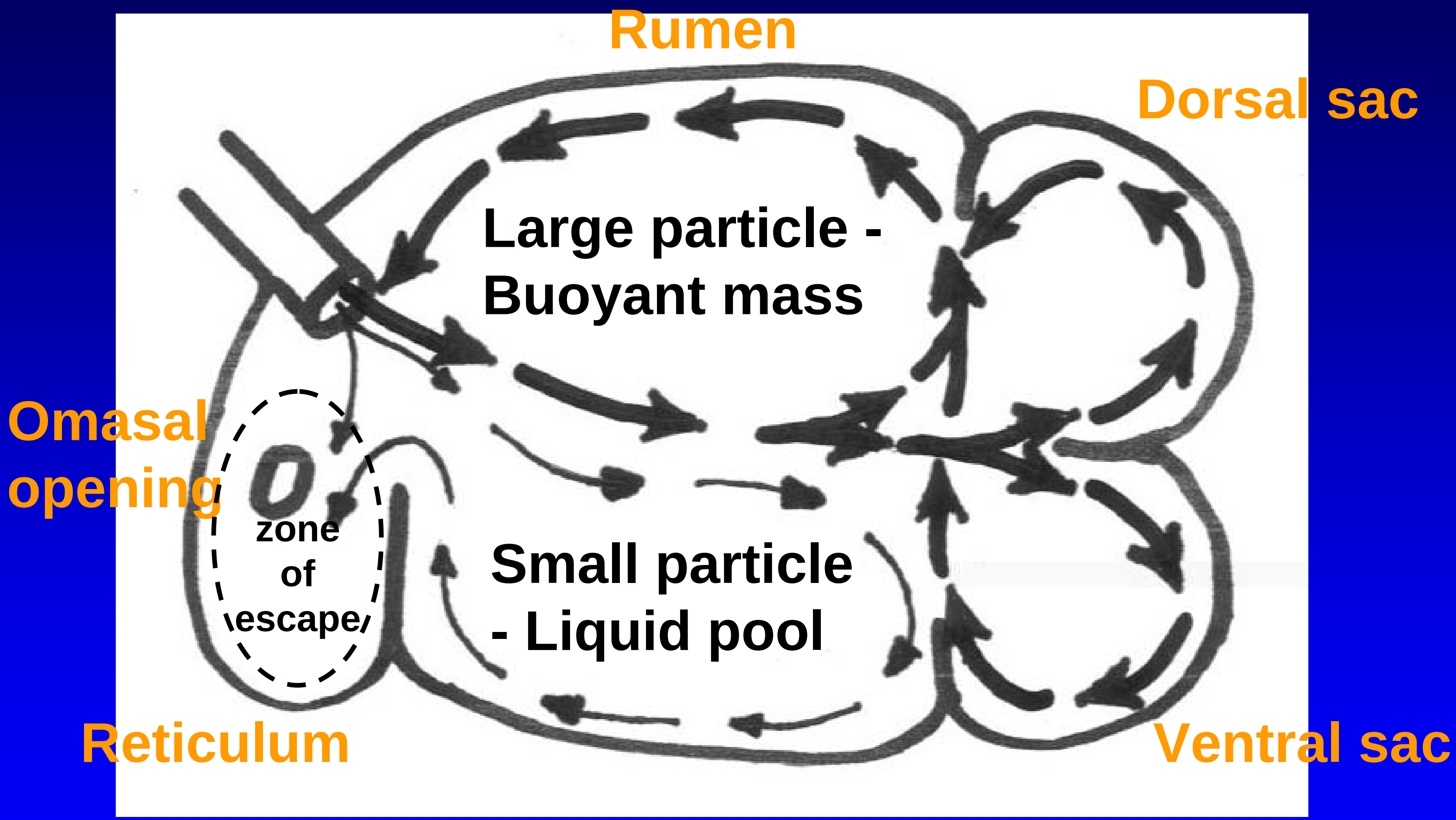
Objectives

- Discuss the physiology of ruminal digestion as it relates to grass utilization
- Describe the crucial aspects of ruminal physiology that must be in rumen models to adequately mimic digestion
- Define and quantify the parameters needed to describe digestion kinetics
- Describe grass growth characteristics
- Present a simple system for using NDF and NDFD to formulate dairy rations

Ruminal Physiology

- Rumen contents tend to be bi-phasic (more evident in low intake, forage-fed cows)
  - Floating mass of large buoyant particles
  - Liquid layer with small dense particles
- Cows swallow large particles which enter the large particle mass
- These particles are regurgitated and ruminated into smaller particles as fermentation progresses (cud chewing)
- Eventually, the small particles enter the "zone of escape" and pass out of the rumen

Movement of Particles in the Rumen



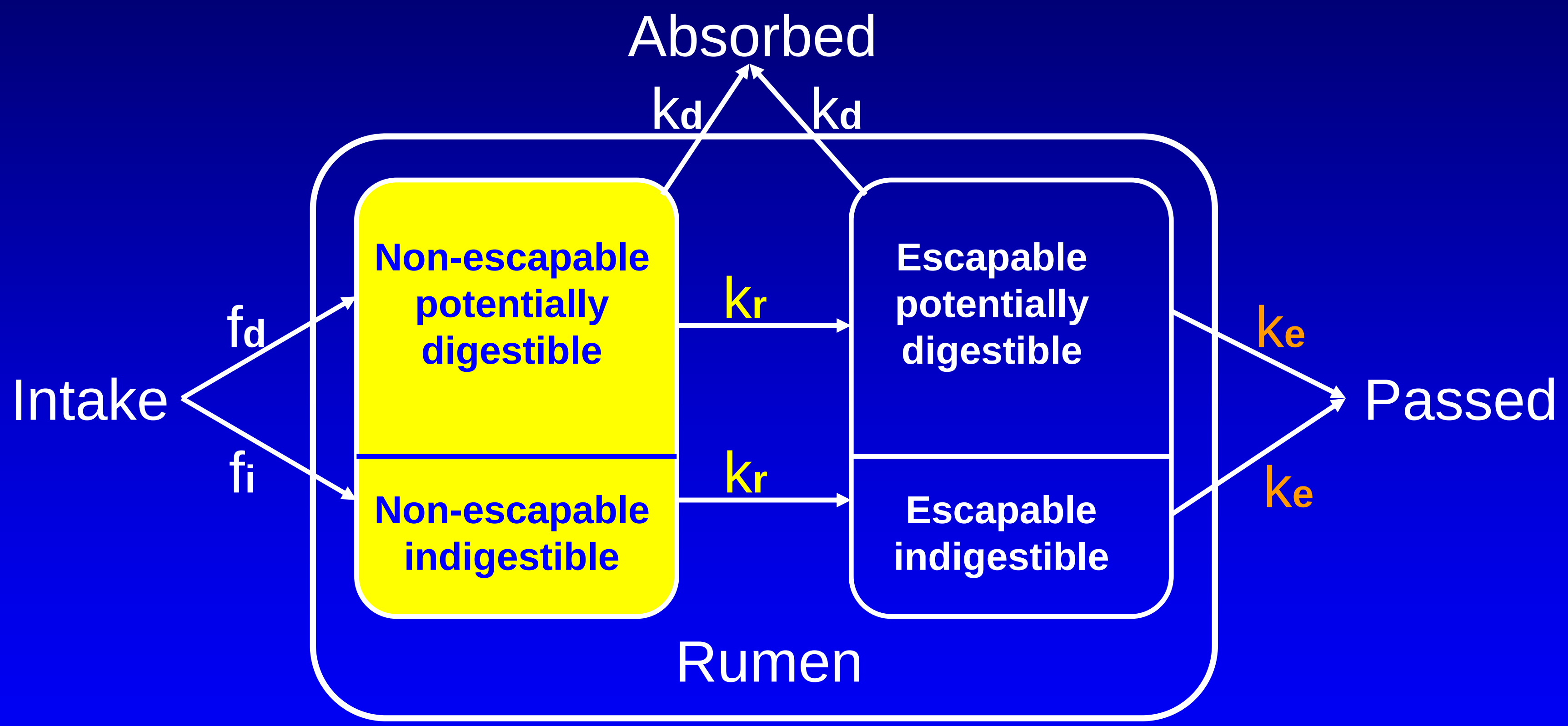
Ruminal Physiology

- Function is ingenious for fiber digestion
  - Selectively retains large, buoyant particles to allow time for fiber to digest
  - Allows small, digested particles to escape
- May not be optimal for concentrates
  - Dense cracked corn particles may quickly escape
- Particle size, hydration and density all play a role in passage

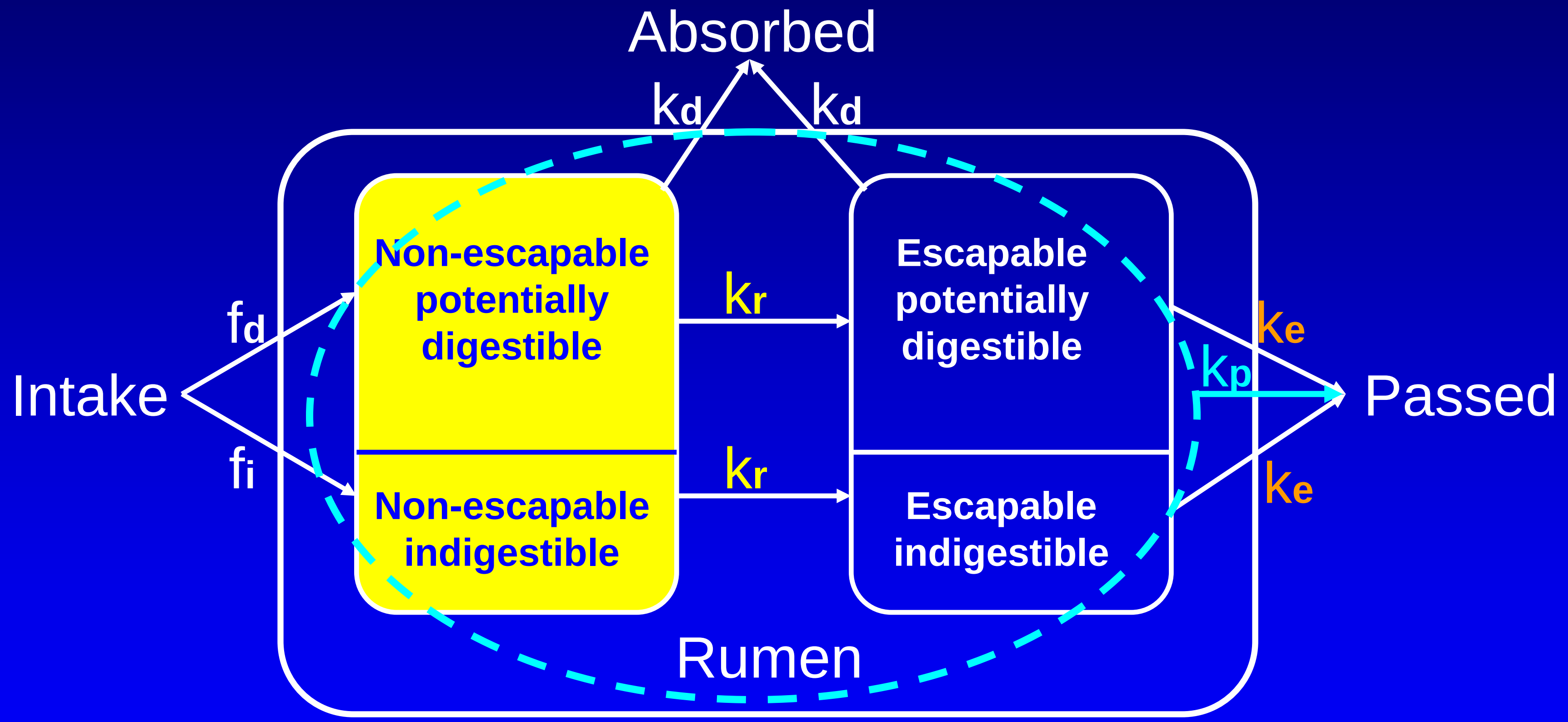
Modeling Ruminal Digestion and Passage

- Digestion and passage are complex, dynamic processes
- Models are simplifications of reality – ruminal physiology
  - Good models include only what is important
  - Cow sense is more important than mathematical expertise
- Essential nature of ruminal passage
  - selective retention of large fiber particles
  - conversion of large particles into small particles
  - passage out of only small dense particles
  - distinctly different flows between liquid and particles

Two-Pool Rumen Passage Model of Allen and Mertens (1988)



Two-Pool Rumen Passage Model of Allen and Mertens (1988) Related to Typical Single-Pool Models

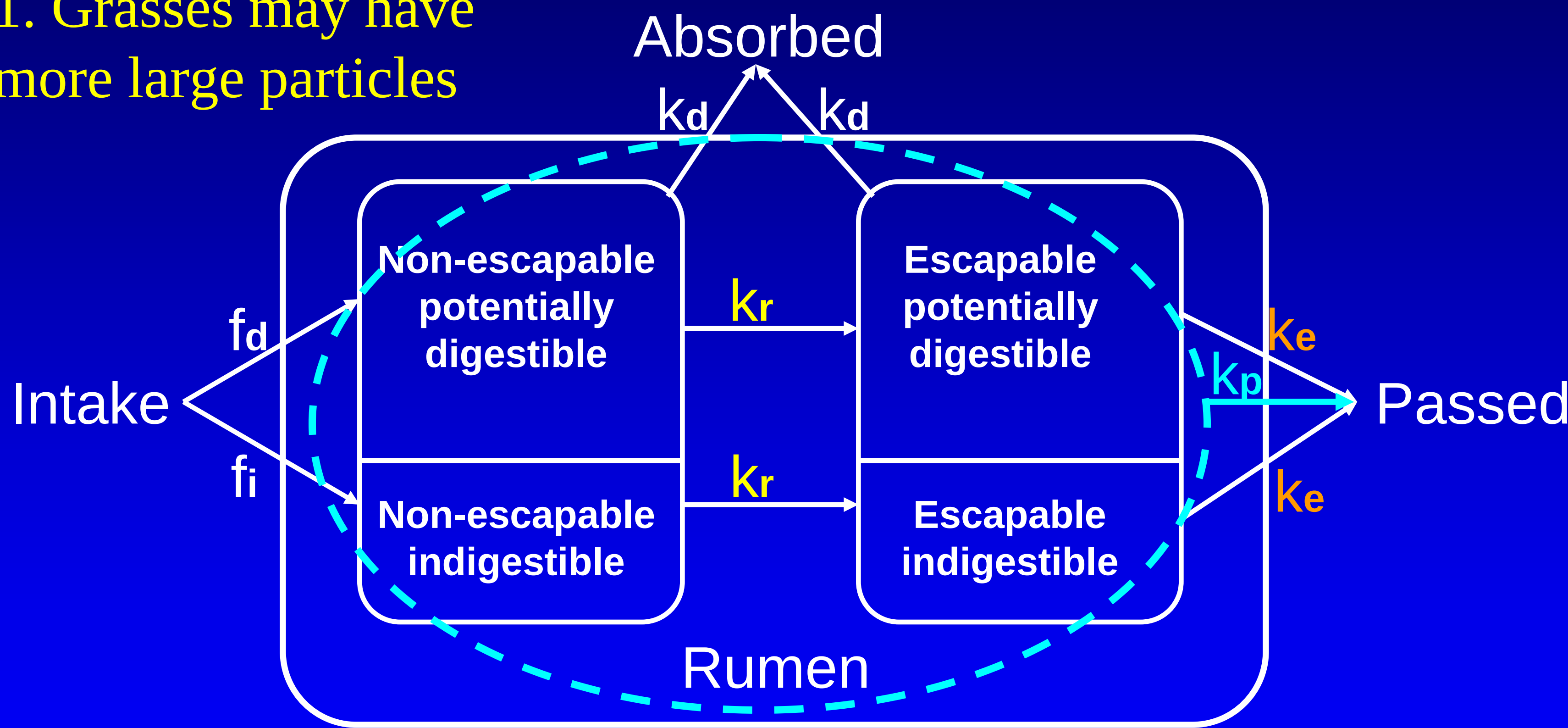


Modeling Ruminal Passage

- Huhtanen et al., (1995) reported that single pool rumen models cannot effectively predict digestibility of fiber
- Lund (2002) demonstrated that proportions of non-escapable and escapable pool is relatively unimportant
- At least a two-pool model and accurate estimate of total retention time is needed to predict digestibility (Huhtanen et al., 1995)

Two-Pool Rumen Passage Model of Allen and Mertens (1988)

1. Grasses may have more large particles



2. Grasses have long slender particles

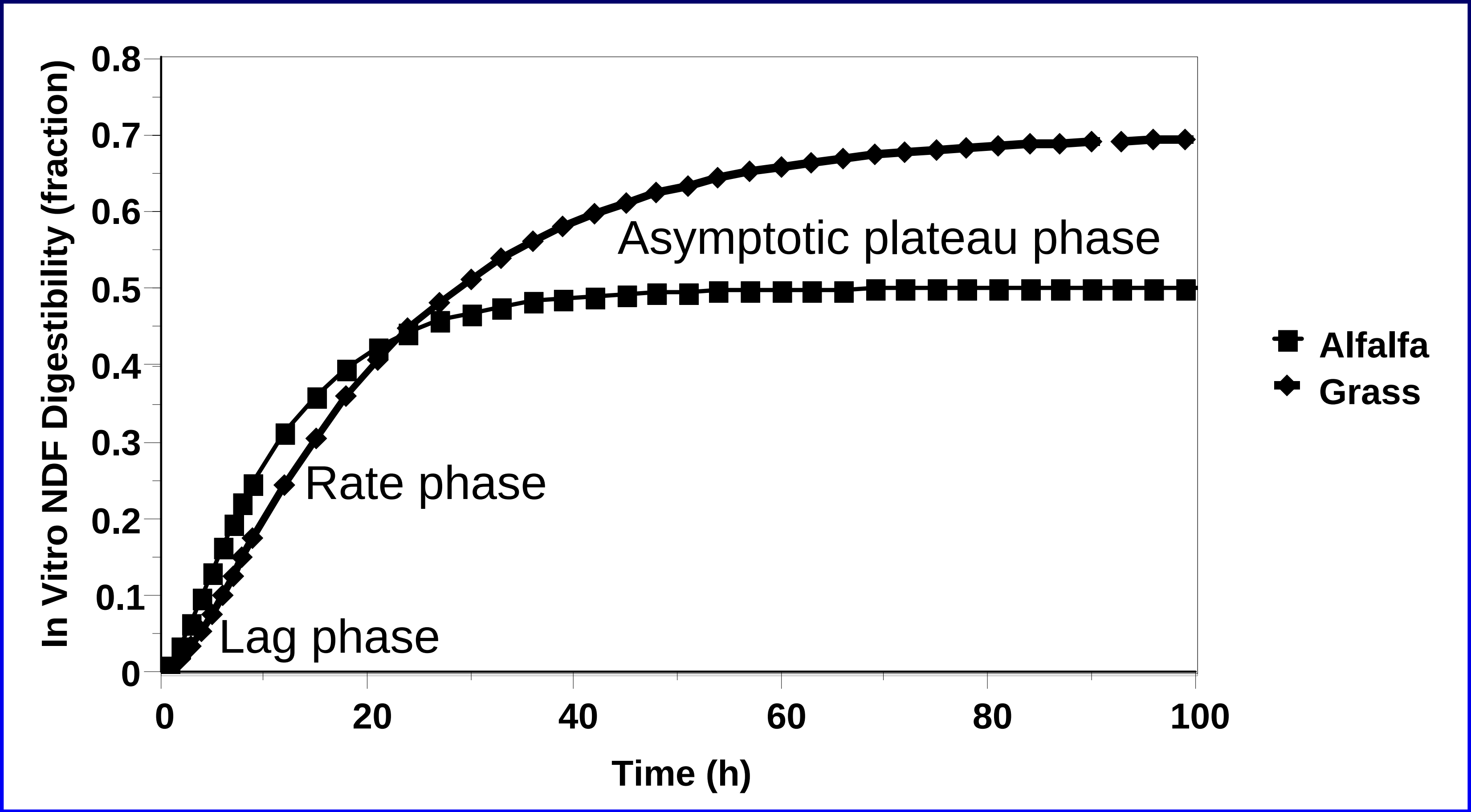
3. Grasses may fracture differently

4. Grasses may have slower passage

Grass Particle Size and Shape

- Proportion of large particles may be underestimated for grasses
  – Long, slender particles pass through vertically shaken sieves
  – Length can be 8-10X the width with vertical shaking (Mertens et al., 1984)
- Long, flexible grass leaves may be formed into a boli easily allowing larger particles to be swallowed initially

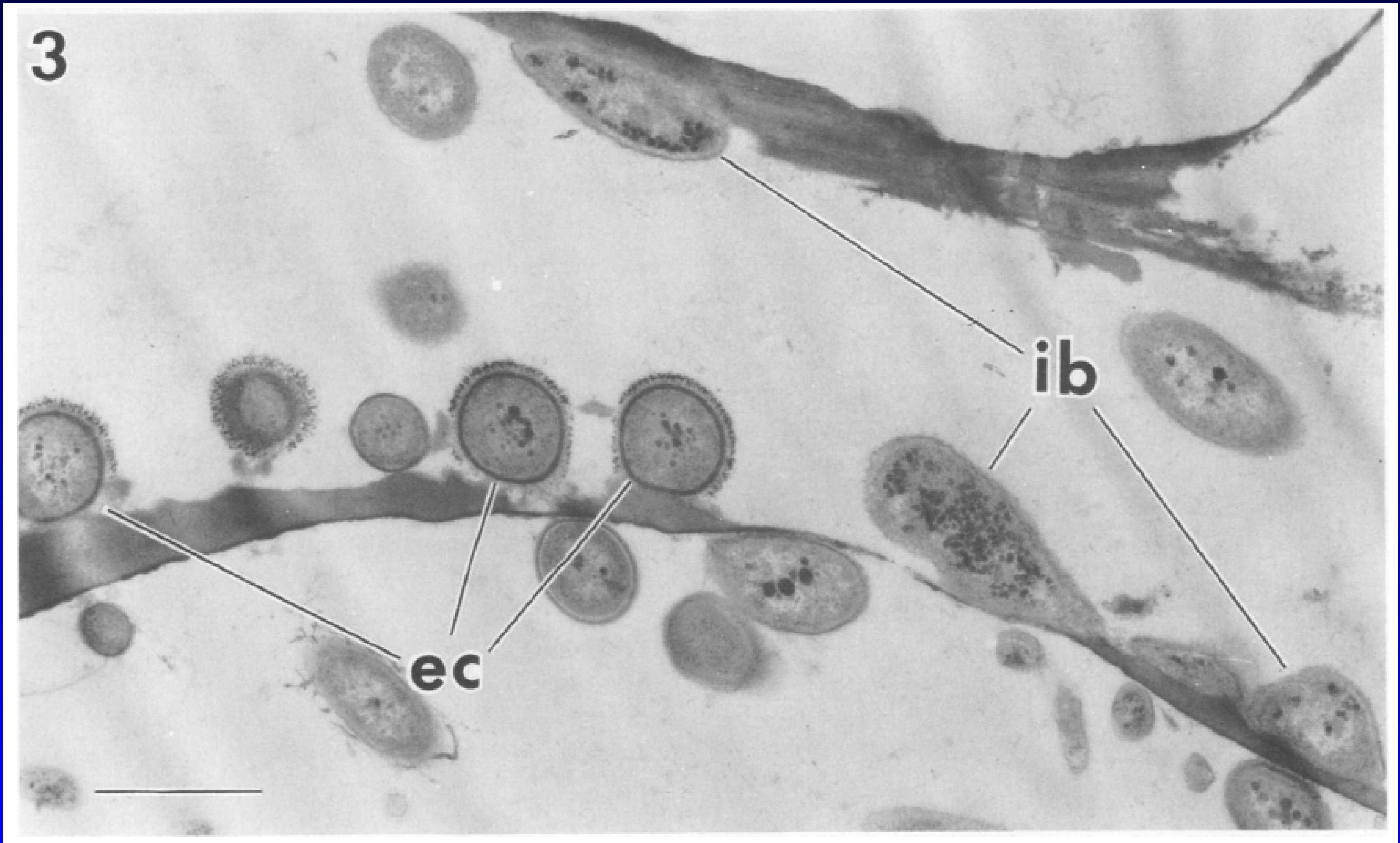
Typical Digestion Curves for Forage Fiber



Digestion Kinetics

- Lag phase
  - Digestion does not begin immediately, but gradually increases to a maximum rate
    - Related to hydration
    - Microbial attachment or association (Akin, 1979, 1980)
    - Microbes differ in the the plant cell types they degrade (Akin and Rigsby, 1985; Jung et al., 2004)
    - Low pH inhibits microbial attachment (Mourino et al., 2001)

Akin (1980)



ec = encapsulated cocci   ib = irregular bacilli

Models of Digestion

- Lag phase
  - Discrete lag time = time before digestion instantaneously begins
    - Over simplification of reality
    - Provides a quantitative measure
    - Long lag times (>4h) indicate in vitro method problems
  - Could be modeled as a sequential two-step digestion process
    - "Unavailable" substrate becomes "Available" for microbial association
    - Available material is digested by microbes

Digestion Kinetics

- Rate of Digestion phase
  - Only a fraction of the fiber is potentially digestible
    - Cannot determine a rate of digestion for total NDF – it is a mixture of potentially digestible and indigestible NDF
  - Substrate characteristics limit digestion
    - Modeled as a first-order process with a constant fractional rate (Waldo, 1969)
    - Rate does not seem to be related to chemical composition
    - Rate of digestion related to environmental differences during plant growth

Digestion Kinetic Parameters
(Smith et al., 1972)

Forage	Rate (h^{-1})	NDF (%)
Average legume	0.116	39.5
Average grass	0.096	54.1
Immature average	0.152	38.8
Mature average	0.060	54.8

Digestion Kinetic Parameters

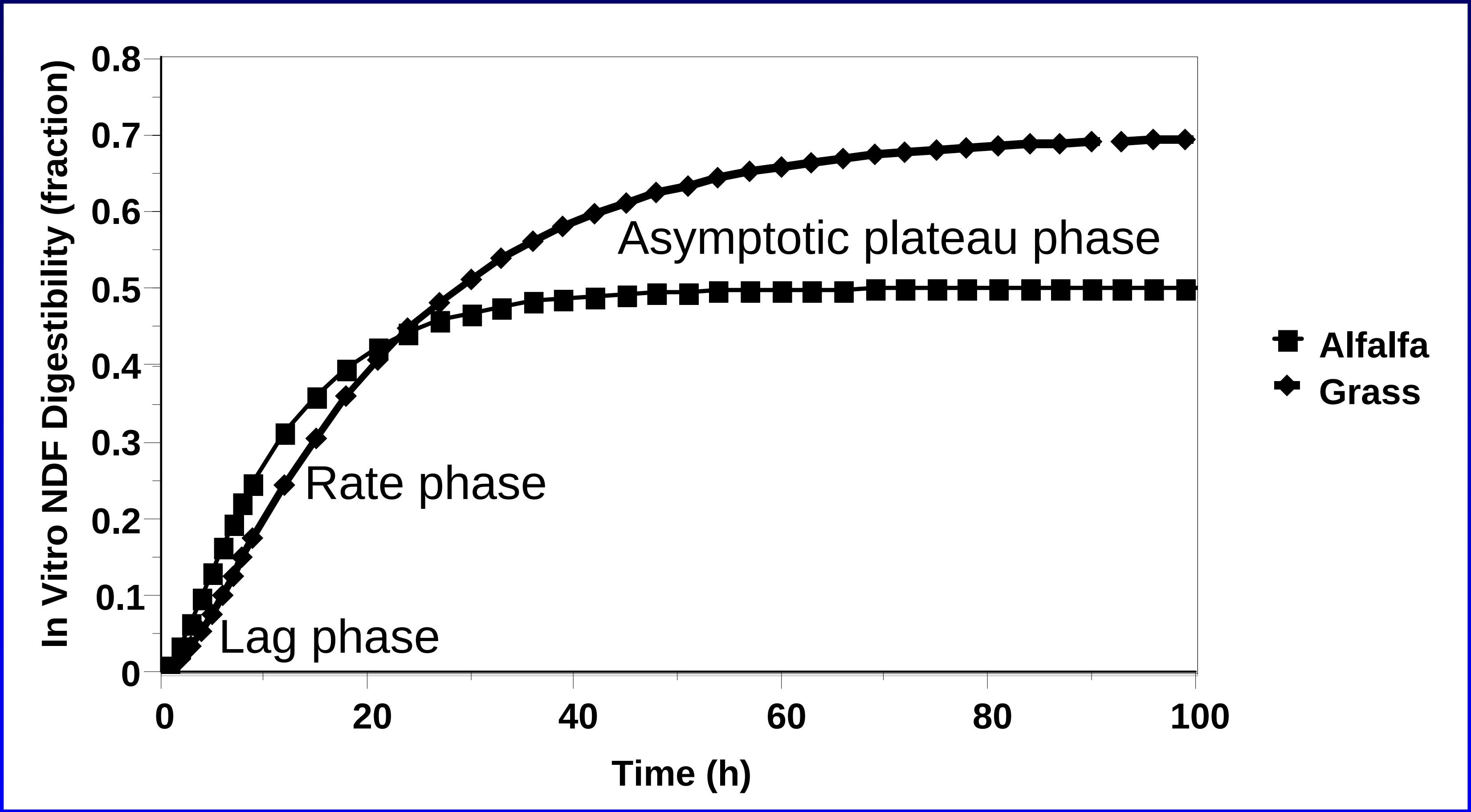
(Twidwell et al., 1988)

Grass stage	Lag (h)	Rate (h^{-1})	iNDF (% DM)	NDF (% DM)
Flag leaf emergence	6.5	0.056	20.4	67.0
14 d after flag leaf	6.0	0.050	29.0	70.6
21 d after flag leaf	6.5	0.044	33.4	72.5

Digestion Kinetics

- Asymptotic, Plateau phase
  - A fraction of fiber is not fermented in anaerobic environments
    - Lack of oxygen limits the end-point of digestion
    - First observed by Huhtanen and Elliot (1956) and Kamstra et al. (1958)
  - Measured by long term fermentations
    - 12-d in situ (bags with small pore sizes)
    - 4 to 6-d in vitro (Wilkins, 1969)
    - 90-120-d methane fermentors
  - Appears to be related to lignification
    - Lignin may indicate the limit for digestion

Typical Digestion Curves for Forage Fiber



Digestible NDF fractions

- iNDF = indigestible NDF will NEVER be digested in an anaerobic environment
- pdNDF = NDF – iNDF = potentially digestible NDF with a fractional rate of digestion
- uNDF = undigested NDF <u>remains after a specified time</u> of fermentation or actual retention time = iNDF + some pdNDF that is not digested
  - Feces contain uNDF (15.2% uNDF vs 9.5% iNDF in feces; Huhtanen et al., 2006)
  - In vitro or in situ fermentation residues < 96 h contain uNDF

Indigestible NDF

- Related to lignin concentration (Smith et al., 1972; Traxler et al., 1998)
- Van Soest et al (2000) postulated that iNDF = 2.4*Lignin (90 to120-d fermentations; Chandler et al., 1980)
- Lignin relationship may not be consistent between primary and regrowth grasses (Nousiainen et al., 2004)
- iNDF as a fraction of NDF is lower for grasses compared to legumes, but is similar per unit of DM

Digestion Kinetic Parameters
(Smith et al., 1972)

Forage	iNDF (% DM)	iNDF (% NDF)	Lignin (% DM)	iNDF/ Lignin
Average legume	20.0	48.8	9.6	2.08
Average grass	19.0	31.3	6.2	3.06
Immature average	10.6	27.6	4.6	2.30
Mature average	28.4	52.6	11.2	2.54

Digestion Kinetic Parameters

(Fales, 1986)

Forage	Lag (h)	Rate (h^{-1})	iNDF (% DM)	NDF (% DM)
Grass				
13/10 C regimen	2.7	0.041	8.8	38.0
20/18 C regimen	3.6	0.037	11.6	42.7
30/27 C regimen	2.8	0.033	16.2	50.1

Digestion Kinetic Parameters

Forage	Lag (h)	Rate (h^{-1})	iNDF (% DM)	NDF (% DM)	Lignin (% DM)
Lechtenberg et al., 1974					
Normal corn stover	3.6	0.050	21.3	43.6	7.1
bmr corn stover	4.0	0.053	19.5	41.4	7.7
Cherney et al., 1986					
Normal sorghum	4.0	0.064	47.1	72.6	9.3
bmr sorghum	4.0	0.083	31.4	72.4	5.5

Digestion Kinetic Parameters

Forage	Lag (h)	Rate (h^{-1})	iNDF (% DM)	NDF (% DM)	Lignin (% DM)
Cherney et al., 1993					
Reed canarygrass	1.2	0.049	16.2	52.5	2.9
Bromegrass	0.7	0.045	13.4	52.6	3.1
Foxtail	1.3	0.046	13.4	49.4	2.7
Tall fescue	1.1	0.044	15.5	50.2	2.7
Timothy	0.5	0.048	13.5	51.3	4.2

Modeling Simulations
Karoline – dynamic cow model

- Forage iNDF concentration and rate of pdNDF digestion were the most important forage parameters (Huhtanen, 2006)
  - Affect digestibility and rumen pools
  - Assuming a constant rumen NDF pool, changing iNDF predicted a 3.0 kg/d greater intake
  - Based on digestibility the intake would be expected to increase 1.0-1.2 kg/d
  - Cows may not eat to a constant ruminal fill

Modeling Simulations
Karoline – dynamic cow model

	iNDF (% of ration DM)		
Response	6.0	10.0	14.0
OMD	.733	.700	.667
NDFD	.727	.673	.620
pdNDFD	.808	.808	.808
NDF pool (kg)	6.76	7.47	8.18
Microbial N (g/d)	227	213	197

Modeling Simulations
Karoline – dynamic cow model

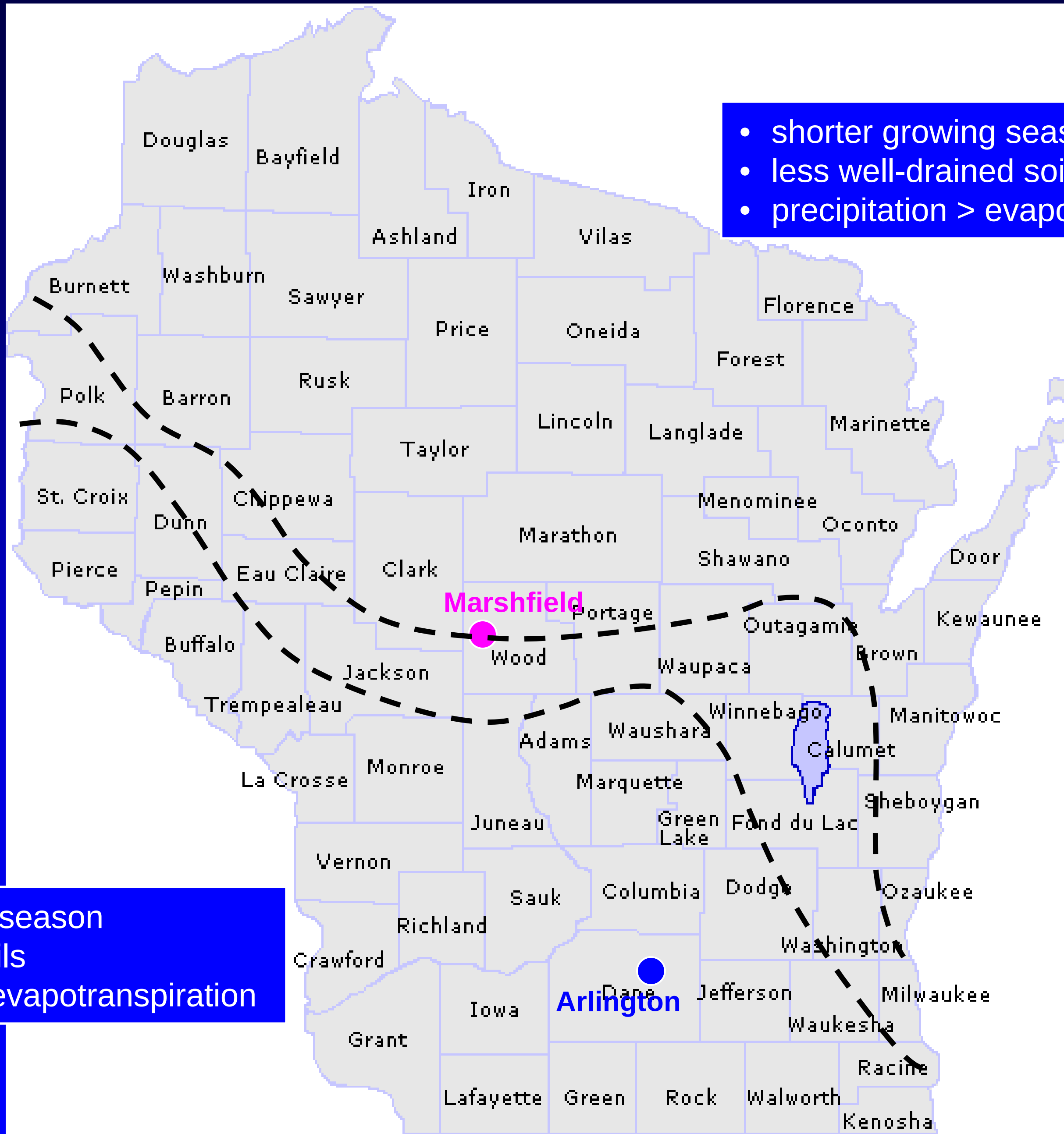
	Rate of pdNDF (h^{-1})			
Response	.04	.05	.06	.07
OMD	.663	.692	.712	.727
NDFD	.615	.663	.697	.720
pdNDFD	.739	.795	.836	.865
NDF pool (kg)	7.91	7.20	6.65	6.25
Microbial N (g/d)	203	216	226	233

Modeling Simulations
Karoline – dynamic cow model

	Ruminal retention time (h)				
Response	30	35	40	45	50
OMD	.657	.676	.691	.703	.713
NDFD	.608	.637	.659	.678	.693
pdNDFD	.730	.764	.791	.814	.832
NDF pool (kg)	6.01	6.59	7.11	7.59	8.03


There's got to be better grass over there.

- shorter growing season
- less well-drained soils
- precipitation > evapotranspiration



Marshfield, WI
is 320 mi north
of Somerset, PA

- longer growing season
- well-drained soils
- precipitation < evapotranspiration

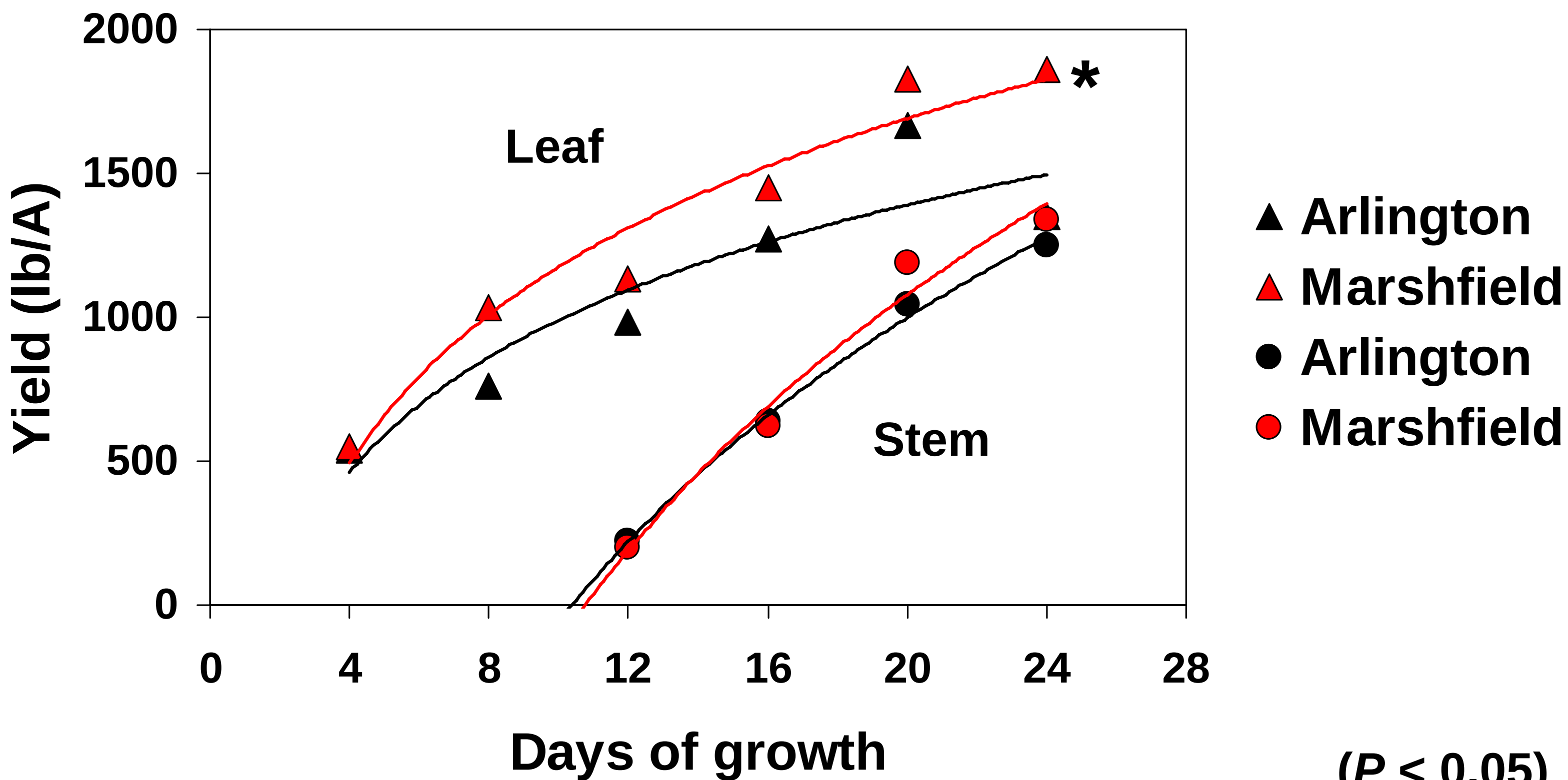
Arlington, WI
is 230 mi north
of Somerset, PA
Roughly equal to
Toronto, ONT.

Grasses:
meadow fescue
orchardgrass
perennial ryegrass
quackgrass
reed canarygrass
smooth bromegrass
tall fescue (soft-leaf)
timothy

After initial clipping, plots sampled:

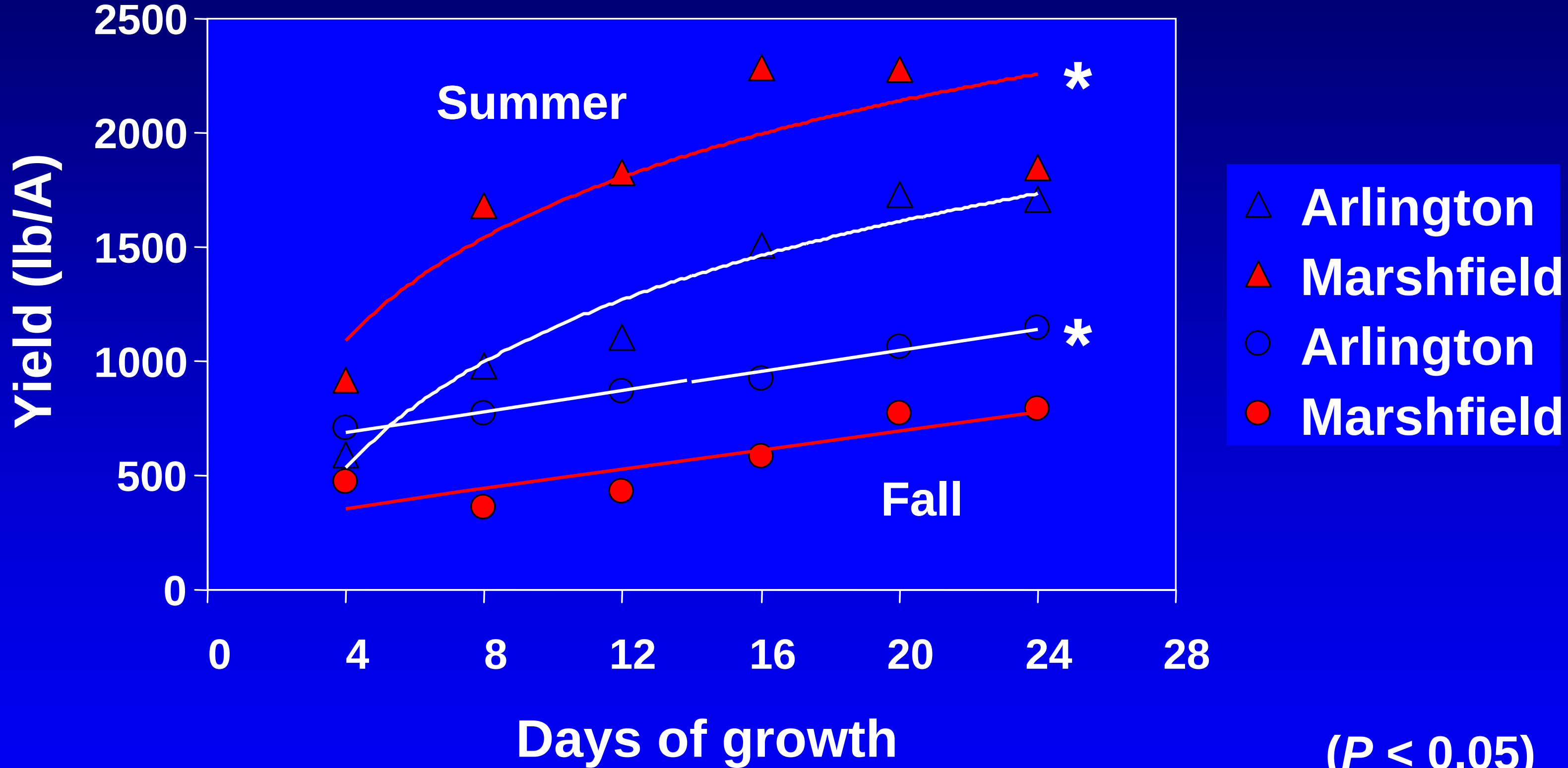
- **every 4 days to 4" residue until 30 days maturity;**
- **in spring (early May), summer (late June), fall (early Sep.);**
- **separated into leaves and stems.**

Spring leaf and stem yield



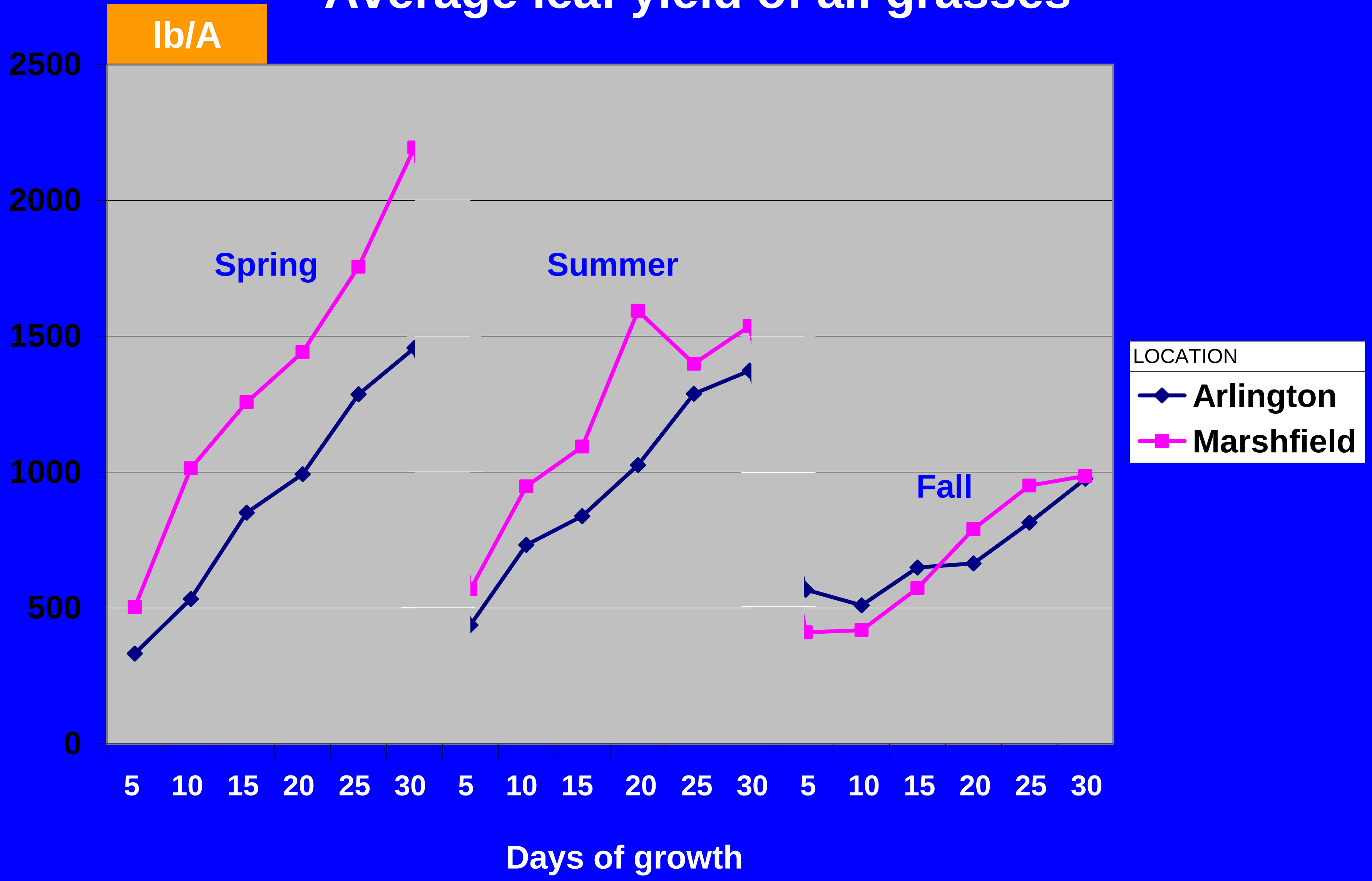
(*P* < 0.05)

Summer and fall leaf yield

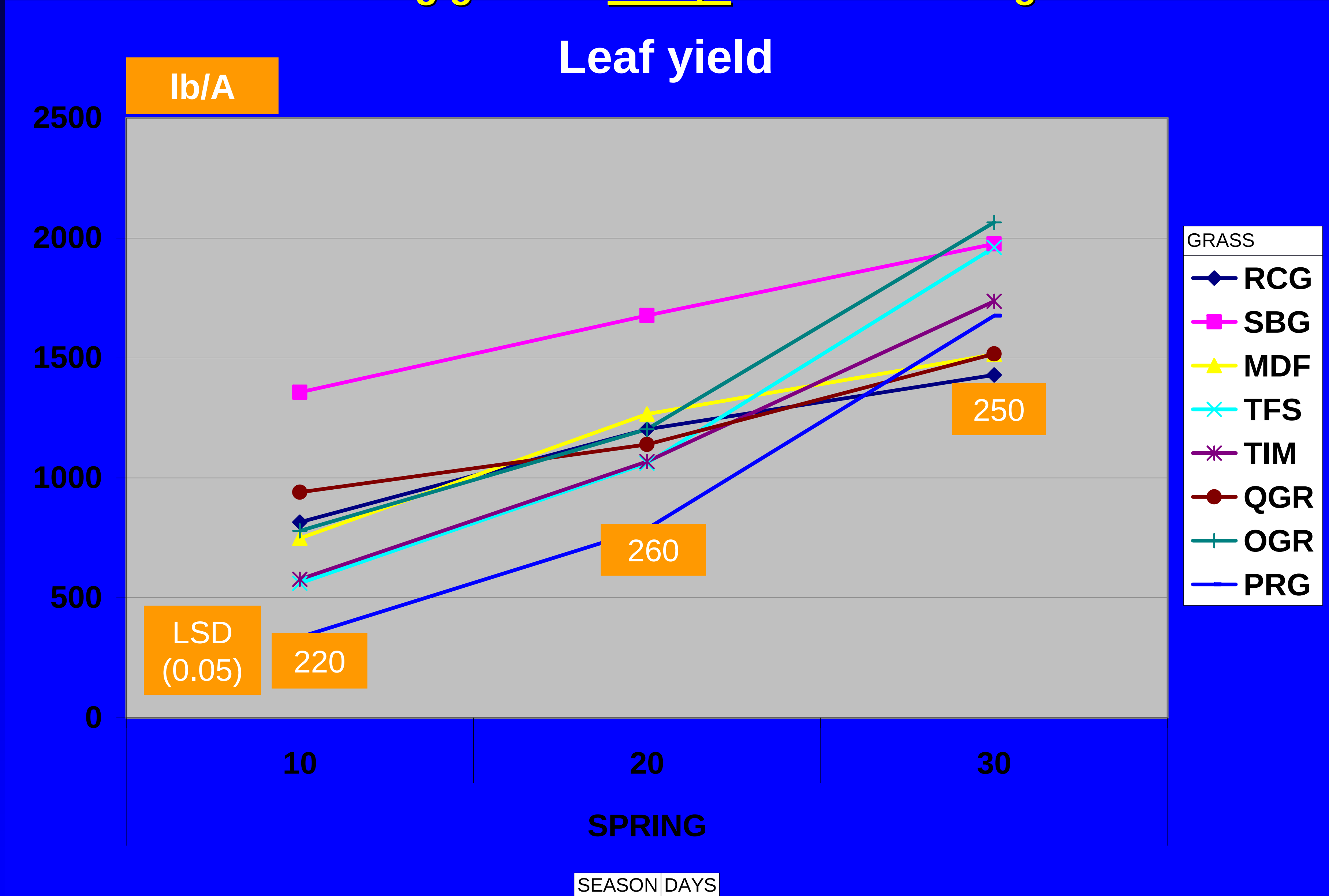


(*P* < 0.05)

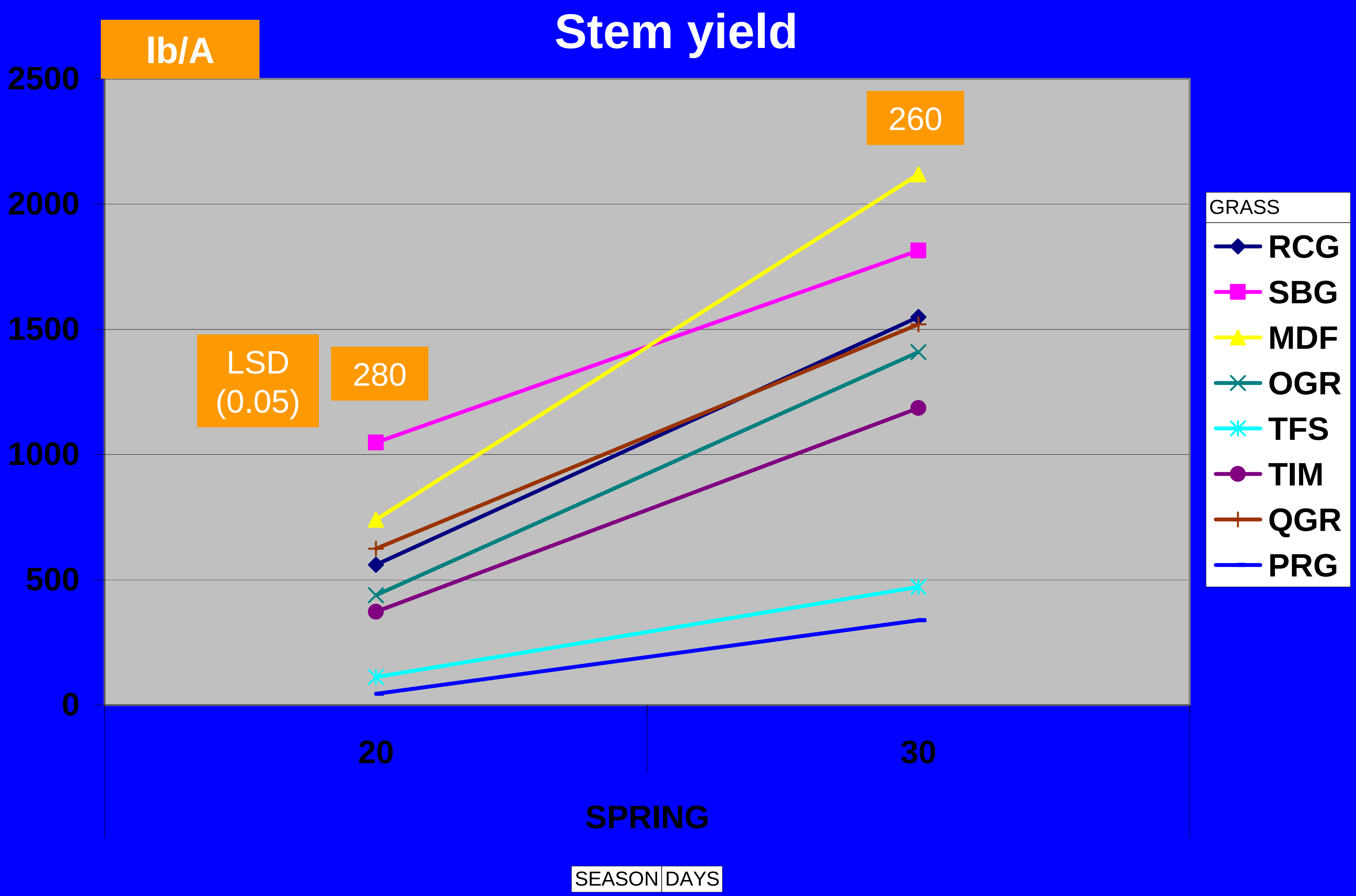
Average leaf yield of all grasses



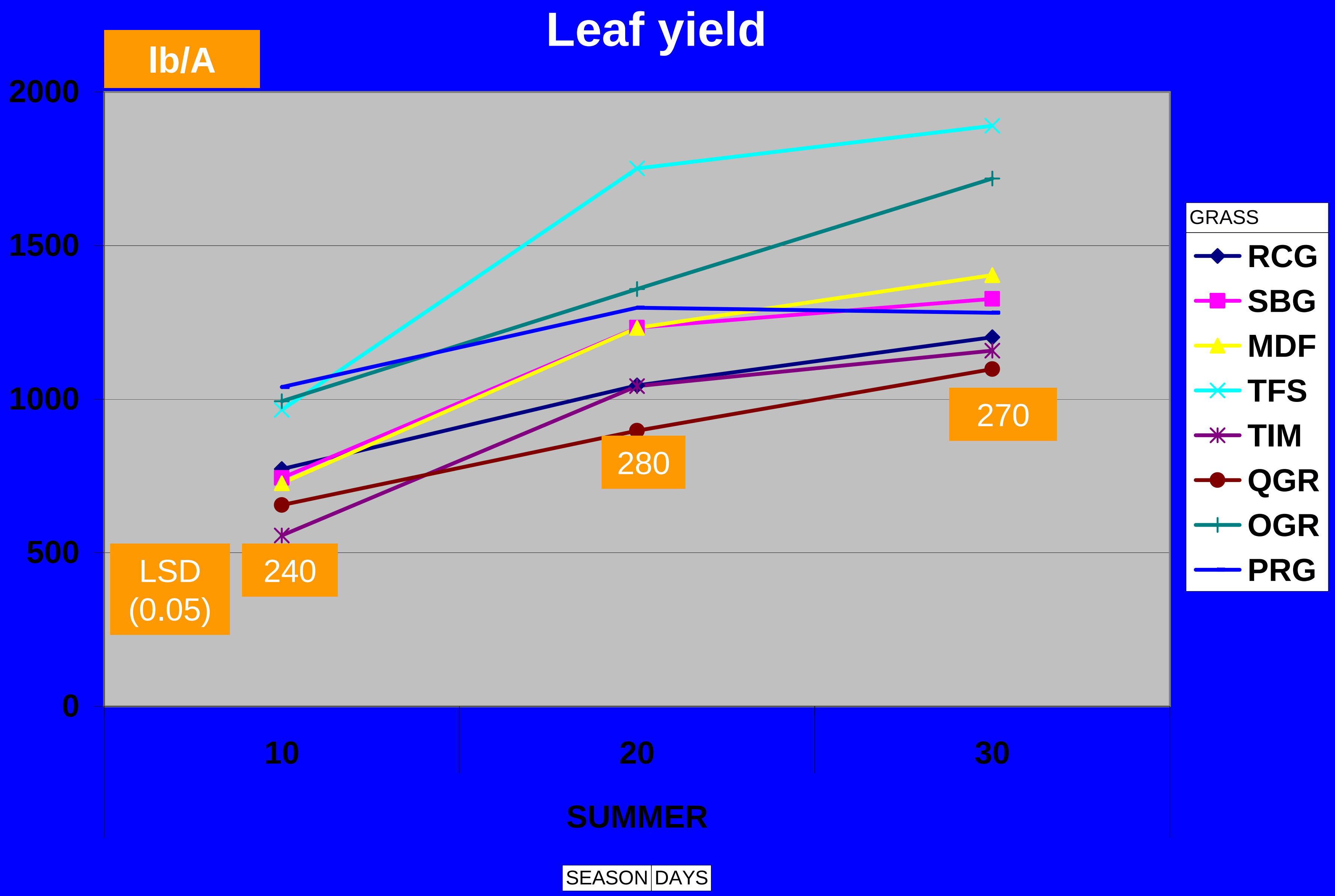
At grazing stage, few differences in spring leaf yield existed among grasses except smooth bromegrass.



Differences in total spring yield were greatly influenced by stem yield, particularly at hay stage.



Soft-leaf tall fescue had the greatest yield during the summer and fall, but also the greatest NDF.



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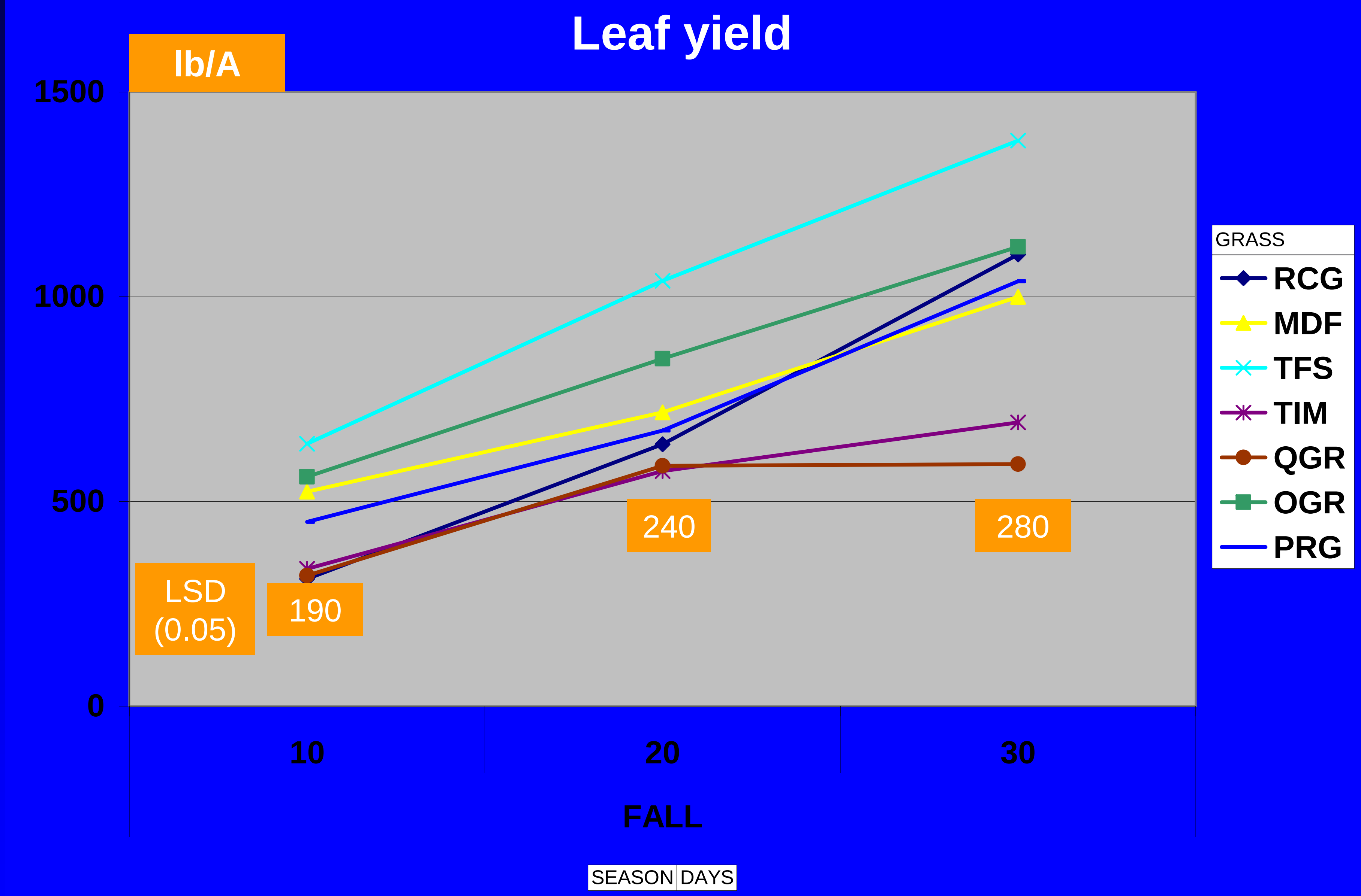

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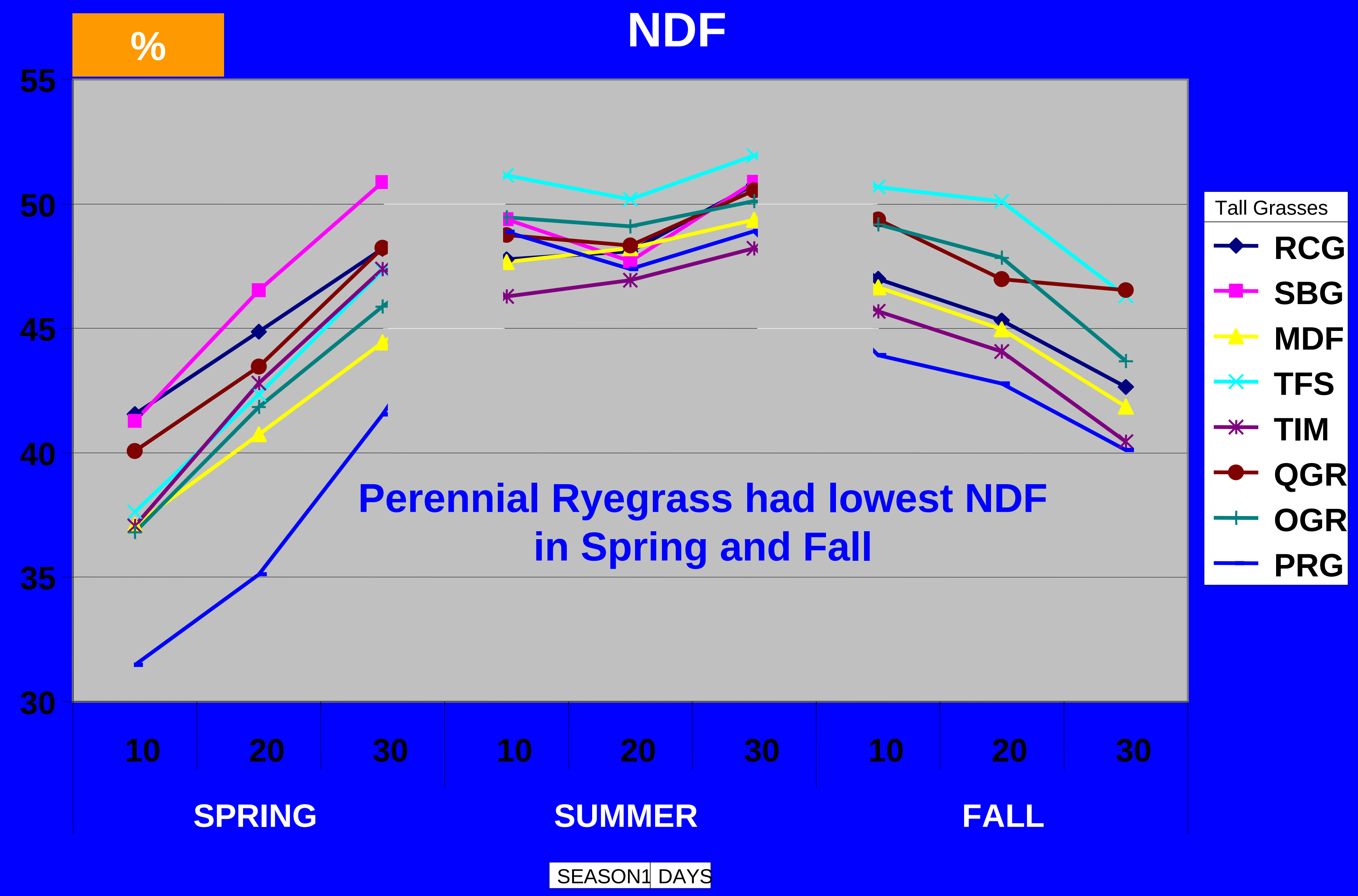

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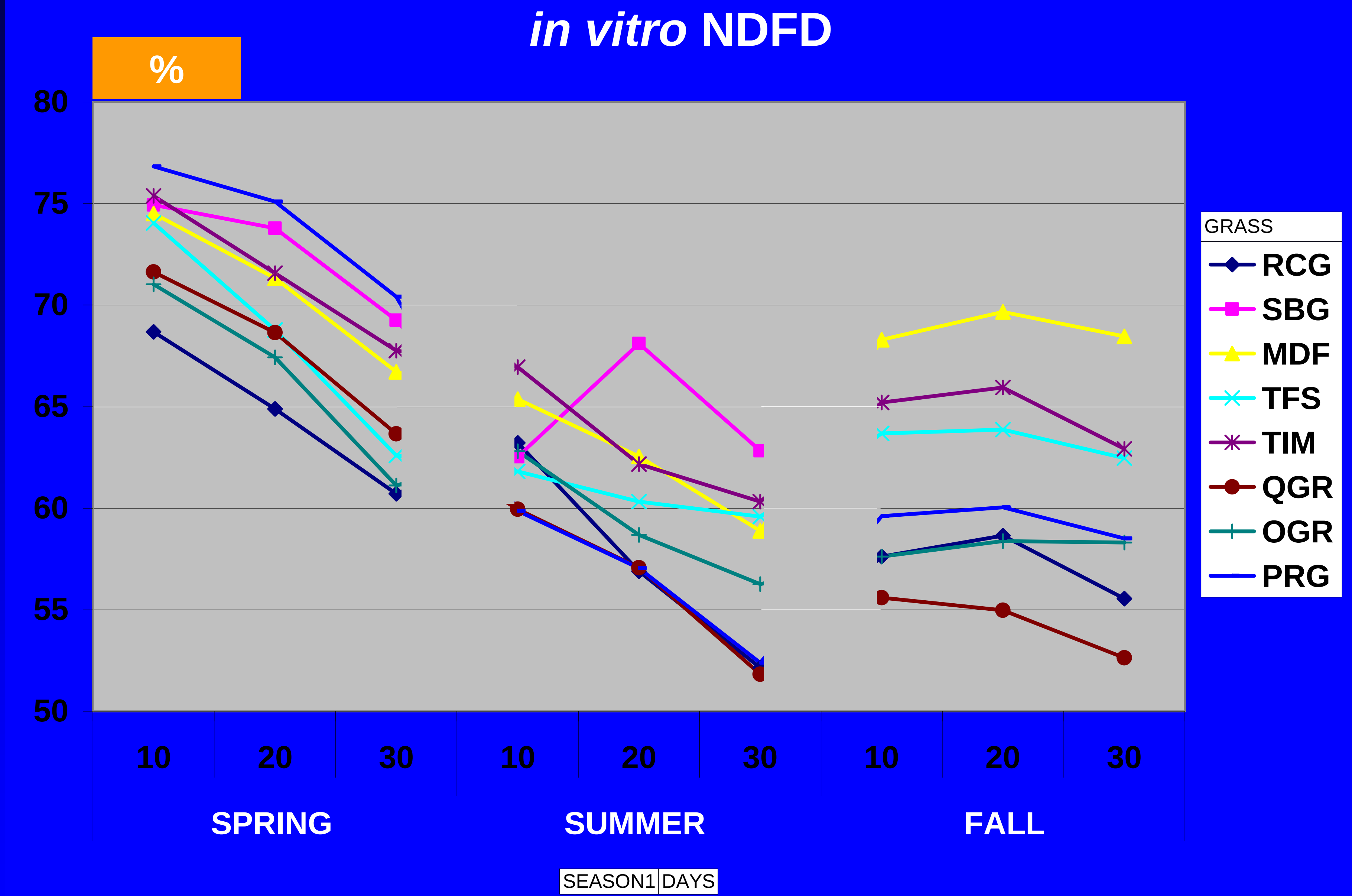
Forage quality of meadow fescue and timothy frequently exceeded that of the other grasses in summer and fall.



Digestibility of Grasses Can Vary Greatly

- Species of grass
- Season of growth
- Production of stems
- Height of cut
- Both NDF and NDFD can vary
- We can use NDF and NDFD to predict DMD using a simple summative equation

Digestibility of Grasses
Simple Summative Approach

- DMD = dNDF + dNDS – endogenous DM loss
  - dNDF = NDFD*NDF(%)
  - dNDS = .98*NDS (%) – 12.9
  - NDS = 100 - NDF
- DMD(%) = NDFD*NDF + .98*NDS – 12.9
- NRC (2001) simply divided NDS into CP, Fat, and NFC

Digestibility of Grasses vs Alfalfa
Simple Summative Approach

Nutrient	Alfalfa High Dig	Grass High Dig	Grass V.High Dig	Grass Incr NDFD
NDF (%)	38.2	54.7	46.4	54.7
NDFD (%)	42.6	60.0	72.4	76.2
dNDF	16.3	32.8	33.6	41.7
NDS	61.8	45.3	53.6	45.3
dNDS	60.6	44.4	52.5	44.4
True DMD	76.8	77.2	86.1	86.1
Endog loss	-12.9	-12.9	-12.9	-12.9
DMD	63.9	64.3	73.2	73.2

Using NDF to Formulate Rations Containing Grasses

- Mertens (1992) developed a system that maximizes forage in the ration for a target milk production using on NDF
- Based on simple theories of intake regulation
  - Cows limit intake of high-energy diets based on energy demand
  - Cows limit intake of high-fiber diets based on fill limitations
- NDFD can be incorporated into the system

Using NDF to Formulate Rations Containing Grasses

- Based on the concept that the upper limit of forage concentration that also maximizes production occurs when dairy cows eat about 1.2% of body weight as NDF
  - Higher concentrate rations also can maximize milk production, but forcing NDF intake about 1.2% often reduces milk production
- NDF can be used to obtain a starting point for For:Conc ratio of dairy rations

Grass Forages: Dynamics of Digestion in the Rumen

QUESTIONS?

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Summary: Take-Home Message

- Rumen evolved to digest forages through a symbiotic relationship with bacteria
- Selective retention of large particles is a key factor in ruminal function
- Ruminal contents consist of an upper large particle mass and a lower liquid layer containing the small particles
- Rumen models should have at least two pools of particles to represent the selective retention of fiber

Summary: Take-Home Message

- Grasses have long slender leaves that may result in slower rates of passage
- Digestion process must be separated into lag phase, indigestible NDF and potentially digestible NDF
- Potentially digestible NDF is the only portion of fiber that can be described by first-order kinetics with a constant fractional rate of digestion

Summary: Take-Home Message

- Indigestible NDF will never be digested in an anaerobic environment
- Undigested NDF measured by animals or in fermentations less than 4 days.
- Indigestible NDF must be measured by long fermentation times or estimated
- Indigestible NDF is correlated to lignin concentration, but the relationship may not be consistent

Summary: Take-Home Message

- Grasses typically have slower rates of digestion, but the indigestible NDF is a smaller proportion of NDF than legumes
- On a DM basis, grasses have similar concentrations of indigestible NDF, but more potentially digestible NDF
- Differences in total spring yield were greatly influenced by stem yield, particularly at hay stage
- NDF and NDFD differs by grass species and season of the year

Summary: Take-Home Message

- Karoline model indicates that indigestible NDF and rate of digestion of the potentially digestible NDF are the most important feed characteristics
- Rumen residence time is also an important factor related to intake and digestibility
- Digestibility at maintenance intake can be estimated by a simple summative equation that contains digestible NDF and digestible neutral detergent solubles

Summary: Take-Home Message

- Grass NDF can be used to formulate rations that will maximize forage for a target milk production
- Changing the digestibility of NDF can be incorporated into the NDF system for formulating rations