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2025 年 第1期 6月刊

值得陶醉的“精神家园”

打破边界的“多元世界”

务实超前的“生态环境”

如影随形的“工作方式”

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经济

ECONOMICS

“北弦书斋”系列活动（十九）

简介：

在本期活动中，我们研读了一篇利用随机干扰试验（RCT）探索缓解财务担忧对工人生产力影响的文章。在全球发展中国家，数亿低收入劳动者长期面临着间歇性就业与收入波动的挑战。尽管主流经济学强调收入提升对脱贫的核心作用，但这篇文章通过一项创新的实地实验揭示了财务压力对工人生产力的负面影响远超传统模型的预测。研究聚焦印度奥里萨邦农村地区 408 名从事季节性制造业的男性工人，在其劳动合同执行期间，通过随机操纵工资支付节奏（分阶段支付 vs. 一次性支付），结合行为经济学与认知科学视角，系统解析了财务压力如何通过心理渠道侵蚀劳动效能。实验结果发现，财务担忧会系统性地占用工人的认知资源，形成“认知税”效应，当财务焦虑缓解后，工人不仅动作更快，决策质量也同步改善。

这项研究首次在真实劳动场景中验证了稀缺性思维的微观机制：财务压力通过激活工人的心理负担，直接消耗个体的心智带宽，导致效率损失。这一发现为贫困研究提供了新的理论视角：缓解流动性约束不仅需要物质支持，更需要对认知资源的解放。通过优化支付节奏、提供债务缓冲等干预措施，可有效释放被财务压力吞噬的心智资源，帮助劳动者在困境中实现更高效能的良性循环。这一发现为理解贫困的动态成因及干预策略开辟了跨学科的新视角，兼具学术创新性与政策实践价值。

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I.引言

财务担忧是影响低收入工人生产力的重要因素。经济拮据带来的心理负担可能导致注意力分散，进而降低工作效率，形成“越贫困越低效”的恶性循环。已有

研究表明，72%的印度农村工人在农闲季节高度担忧财务状况，且半数人承认工作时受财务问题困扰。为验证缓解财务担忧能否提升生产力，本文以印度奥里萨邦 408 名按件计酬的制造业工人为样本，设计了一项随机干预实验：实验组提前获得部分工资以缓解流动性约束，对照组则按常规周期领取薪酬。通过追踪工人支出模式、自我报告及生产力数据，探究通过现金注入缓解财务担忧对工作表现的影响。

实验结果显示：第一，提前支付显著降低了工人的财务担忧。实验组在获得现金后立即偿还债务并增加家庭必需品支出，债务偿还概率提升 222%，家庭支出增长 70%；第二，财务担忧缓解显著提高了生产力。实验组日产量增加 6.9%，且注意力失误减少 0.08 个标准差，表明工人既能加速生产又能减少错误；第三，干预效果集中于经济更困难的工人群体，其生产力提升幅度达 13%，注意力改善程度是整体样本的两倍。

本文的创新主要体现在两方面：其一，首次在真实工作场景中验证财务担忧通过心理机制影响生产力的因果关系，揭示了“财务担忧导致注意力下降，进而降低工作效率，最终加重经济困境”的循环模式；其二，通过测量生产过程中的注意力痕迹（如缝合错误次数），构建了客观的认知负荷指标，突破了传统自我报告数据的局限性。这些发现为优化薪酬结构、设计减贫政策提供了新依据，同时拓展了行为经济学关于稀缺性认知的研究边界。

II.研究背景与实验设计

A 背景：财务担忧

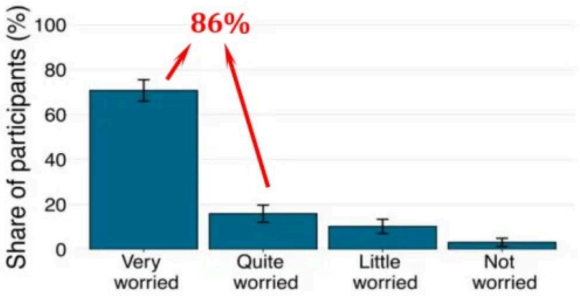
印度奥里萨邦低收入工人在农闲季节面临严峻的财务压力与流动性约束。研究样本中，68%的工人身负未偿债务，54%依赖杂货店赊账维持基本消费，64%的工人无法紧急筹集相当于四日工资的资金（1000 卢比）。财务压力渗透至日常生活的方方面面：86%的工人对财务状况感到焦虑，52%每日至少一次被财务问题困扰，43%的焦虑状态持续数小时。开放式访谈显示，债务催收、子女需求拒绝与突发医疗支出是主要的压力源，工人常因无力应对而产生愧疚与无助感。

这种财务困境直接影响工作表现。基线调查发现，50%的工人在制作餐盘时分心于财务问题，导致注意力分散。质性研究进一步揭示，工人在家庭场景中积累的心理负担（如面对债权人羞辱或拒绝子女请求）会延续至工作场所，形成持续性认知负荷。尽管工资收入可预期，但流动性短缺使工人难以缓解即时压力，唯有实际现金到账才能有效降低焦虑水平。这一现象为本文的实验设计提供了理论基础：通过提前发放工资形成短期流动性冲击，分离财务担忧影响工人生产力的纯心理效应。

B 实验参与者

为探索减轻财务担忧对工人生产力的影响，该研究团队在印度东部的奥里萨邦（Odisha）招募了 408 民男性工人开展实地实验。实验招募的参与者要求年龄在 18 至 55 岁之间、能说流利的当地方言奥里亚语、定期从事雇佣劳动并且不是移民，入组后所有人被随机分配到实验组和对照组。实验时间设置在 2017 年和 2018 年的 3 月至 6 月，这正是当地居民“青黄不接”的季节，农业生产工作进入淡季，由于收入的来源减少，工人们在实验开始时就面临着巨大的经济压力。在基线，有 86% 的工人表示对自己的财务状况感到担忧或非常担忧（Panel A）。最常见的两个担忧来源是日常开支和贷款（Panel B），71% 的工人背负着未偿还的债务；此外，有 66% 的工人表示，在紧急情况下，他们很难拿出 1,000 卢

比。

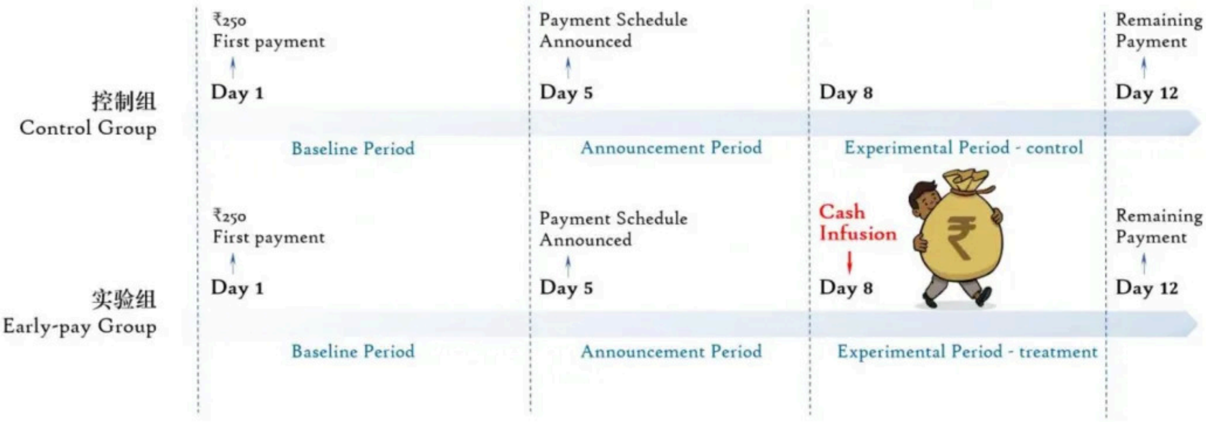


Panel A：Intensity of worries

Panel B：Triggers of financial worries

C 实验场景与工作任务

与当地的承包商合作，研究团队雇佣实验参与者为餐馆制作一次性婆罗树叶(Sal tree) 盘子，这份临时工作为期 12 天。工人们通常从上午 8 点或 9 点开始，下午 2 点至 5 点结束，在模式轮中每天工作 5 小时。工人在自己的个人工作区单独工作，与其他工人保持身体距离；这限制了工人之间的互动范围，以最大限度地减少工作中的产出比较或社交对话。实验过程设计如下：



第1天上班时：所有工人都接受培训，培训工资为250卢比，在正式工作阶段，工资由基本工资和计件工作组成。同时，工人们会被告知有些工人可能会分两次而不是一次收到工资，并且每位工人的具体付款时间表将在第5天公布。

第5天早上：每位工人都会被告知何时收到工资。

第8天：实验组收到从第2天到第8天的工资，控制组未获得任何工资。

第12天：临时工作结束，所有工人都收到了尚未结算的工资。

C 实验操纵

该实验的核心操纵是财务压力，实验设计的巧妙之处在于通过改变工资支付的时间，人为制造了处理组的工人提前获得**现金流入**的情境，从而缓解其短期流动性约束和财务压力，同时保持其他工作条件完全一致。这种设计使得研究者能够直接观测到财务压力缓解对工人行为以及生产效率的影响，有效分离出心理机制的作用。此外，第5天和第8天之间的“公告期”能够测试工人是否会立即对其付款时间表做出反应，即我们可以看到在**预期现金**到达时，生产力有无任何变化。对于流动性受限的工人来说，现金的实际到来可以减轻财务压力，而收入预期可能不足以缓解财务压力。在没有临时工资处理的补充实验中，研究者还操纵了计件工资变化和启动效应，以观察两项因素对工人行为的影响。

III.核心变量测度

A. 产量（Output）

衡量产量的主要指标是按小时计算的合格叶板数量。要获得报酬，工人们制作的盘子必须满足以下要求：(i) 满足最小尺寸要求；(ii) 没有孔洞或缝隙，以便盛放食物（例如咖喱）时不会漏出；(iii) 所有叶柄都被其他叶子覆盖；(iv) 构成盘子外圈（周长）的叶子应放在构成盘子内圈的其他叶子之上（如下图所示）。

Pic from https://www.naturallybengal.com/?craft=sal

B. 专注度指标（Attentiveness Index）

制作一个叶子盘子需要将不规则大小的叶子组装成一个干净的圆圈，要有效

做到这一点，需要规划（叶子如何组合在一起）和专注（确保每个针脚都符合计划）。因此，研究者测量了每个工时时段每块盘子的专注度标志（如下图）：

a) “双孔”的数量(工人为了拆下一片叶子来纠正错误而从盘子上拆下一针的明显迹象)
b) 使用的叶子数量
c) 使用的针数

这三项指标使用控制组在工资发放后的产量(平均值和标准差)进行标准化，然后取平均值以创建专注度指数。接下来，研究者对该指标进行了反转，这样指数上的值越高，专注度就越高（即双孔、叶子数或针脚数越少）。此外，研究者还创建了一个“专注度高”的指标，定义为指数值大于中位数，以显示除线性指标之外的稳健性。

IV.实证结果

A. 数据内部有效性

样本中的典型工人约 40 岁。几乎所有工人都已婚（98%）且有孩子（89%）；75%的工人报告日常临时劳动是他们全年主要的收入来源，平均工人在过去一个月找到九天的有薪工资工作。

为了计算基线财富和流动性的汇总指标，本文使用了四个二元变量：住房质量（即住在非泥土房屋中，且采用耐用材料建造）；拥有农田；没有依赖商贩或邻居通过赊账方式获得食品或日常用品；以及在紧急情况下能够筹集 1000 卢比。并对这四个二元变量进行简单平均，形成财富指数。如果某一指标因未回复而缺失（占样本的 1.5%），则该指数是剩余三个指标的平均值。同时，本文使用对应二元指标来分析，其中该指标等于 1，如果工人的财富指数值弱大于样本工人中的中位数值。

由于行政疏忽未获得一名工人的基线调查数据；因此，使用这种财富异质性的分析样本为 407 名工人（而非 408 名）。

B. 实证模型

本文的实证模型如下：

$$
\begin{aligned}
y_{irdh} = {} & \beta(\text{Cash}_i \times \text{Post-Pay}_{ird}) \\
& + \gamma(\text{Cash}_i \times \text{Announcement period}_{ird}) \\
& + \theta(\text{Post-Pay}_{ird}) + \mu(\text{Announcement period}_{ird}) \\
& + X'_{ir}\lambda + \delta_r + \varepsilon_{irdh},
\end{aligned}
$$

其中 y_{irdh} 是工人 i 在轮次-波次 r 的第 d 天第 h 小时的结果。$Cash_i$ 是一个二元指标，表示个体是否属于临时支付处理组。$Post\text{-}Pay_{ird}$ 是一个二元指标，在工人所属波次的临时支付发放后的日子里等于 1，其他情况下为 0。公告期 $Announcement\ period_{ird}$ 在支付时间表公告后直到临时支付发放期间为 1，其他时候为 0。回归控制了轮次-波次（即层次）固定效应。最后，X_{irmh} 是控制变量（包括教育年限、婚姻状况、子女数量、能否读报、过去 7 天的工作天数、过去 30 天的工作天数、财产状况、是否贷款等），使用 Belloni、Chernozhukov 和 Hansen（2014）提出的后双重选择 LASSO 程序选择。

本文关注的系数是β，表示临时支付的平均处理效应（即处理组和对照组之间的差异）。除此之外，γ估计公告效应——即在工人得知支付时间表后但在发放任何资金之前，处理组和对照组行为的差异程度。本文还通过基线财富指数来检查处理效应的异质性。

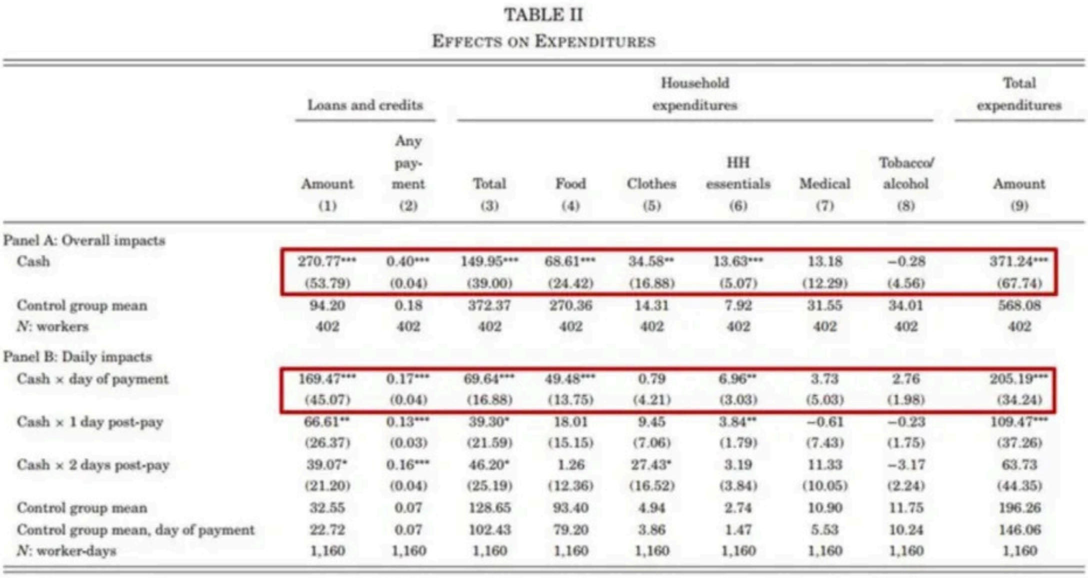
对于一些补充分析，例如支出、工作期间自报告的专注度或早餐测量，结果仅在结束时收集。在这些分析中，本文运用简单的回归比较处理组和对照组:

$$
y_{ir} = \beta \text{Cash}_i + X'_{ir}\lambda + \delta_r + \varepsilon_{ir},
$$

其中 y_{ir} 是工人 i 在轮次-波次 r 的结果，其他协变量如上所定义。在大多数情况下，本文使用后双重选择 LASSO 程序选择基线控制变量。

C. 实证结果 1：对财务压力(Financial Strain)的影响

TABLE II
EFFECTS ON EXPENDITURES

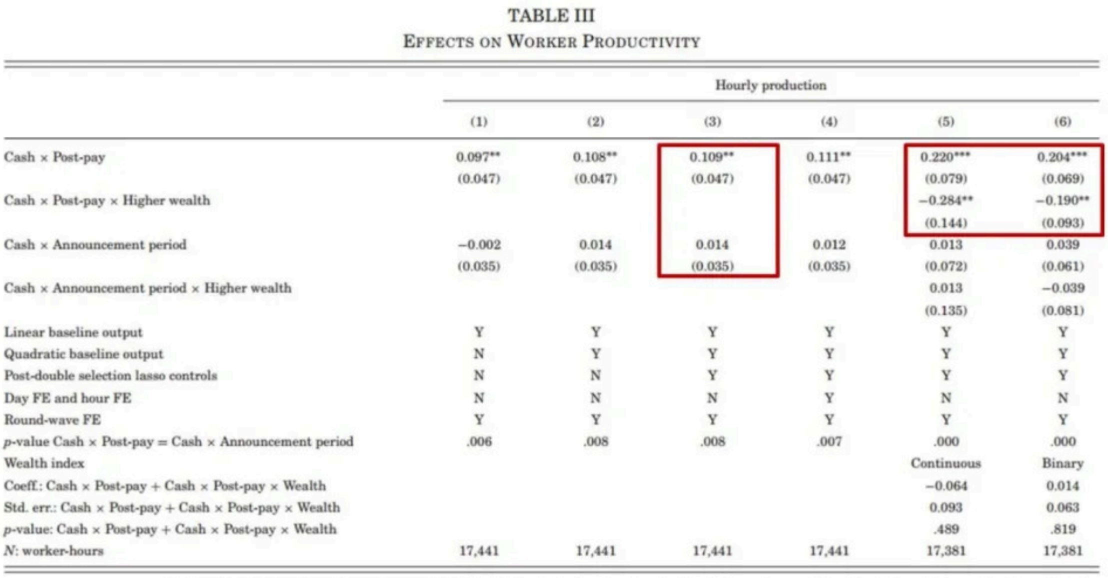


	Loans and credits		Household expenditures						Total expenditures
	Amount (1)	Any payment (2)	Total (3)	Food (4)	Clothes (5)	HH essentials (6)	Medical (7)	Tobacco/alcohol (8)	Amount (9)
Panel A: Overall impacts									
Cash	270.77***	0.40***	149.95***	68.61***	34.58**	13.63***	13.18	−0.28	371.24***
	(53.79)	(0.04)	(39.00)	(24.42)	(16.88)	(5.07)	(12.29)	(4.56)	(67.74)
Control group mean	94.20	0.18	372.37	270.36	14.31	7.92	31.55	34.01	568.08
N: workers	402	402	402	402	402	402	402	402	402
Panel B: Daily impacts									
Cash × day of payment	169.47***	0.17***	69.64***	49.48***	0.79	6.96**	3.73	2.76	205.19***
	(45.07)	(0.04)	(16.88)	(13.75)	(4.21)	(3.03)	(5.03)	(1.98)	(34.24)
Cash × 1 day post-pay	66.61**	0.13***	39.30*	18.01	9.45	3.84**	−0.61	−0.23	109.47***
	(26.37)	(0.03)	(21.59)	(15.15)	(7.06)	(1.79)	(7.43)	(1.75)	(37.26)
Cash × 2 days post-pay	39.07*	0.16***	46.20*	1.26	27.43*	3.19	11.33	−3.17	63.73
	(21.20)	(0.04)	(25.19)	(12.36)	(16.52)	(3.84)	(10.05)	(2.24)	(44.35)
Control group mean	32.55	0.07	128.65	93.40	4.94	2.74	10.90	11.75	196.26
Control group mean, day of payment	22.72	0.07	102.43	79.20	3.86	1.47	5.53	10.24	146.06
N: worker-days	1,160	1,160	1,160	1,160	1,160	1,160	1,160	1,160	1,160

Table II 列出了临时工资发放对后续三天工人支出的影响，分别对贷款支出、家庭购买支出和总支出三个变量分析。回归结果表明：（1）相比于控制组工人，临时工资发放显著提高了处理组工人的贷款偿还金额和概率（Panel A）；（2）临时工资发放显著提高了处理组工人的家庭购买支出（Panel A）；（3）临时工资发放显著提高了处理组工人的总支出（Panel A）；（4）临时工资发放对处理组工人后续支出的提升效应在工资发放的当天效果最强（Panel B）。综上可知，临时工资的发放可以立刻对处理组工人的支出产生正向影响，帮助工人偿还债务以及满足家庭日常开支，从而改善工人的财务压力。

D. 实证结果 2：对生产率（Productivity）的影响

TABLE III
EFFECTS ON WORKER PRODUCTIVITY



	Hourly production					
	(1)	(2)	(3)	(4)	(5)	(6)
Cash × Post-pay	0.097**	0.108**	0.109**	0.111**	0.220***	0.204***
	(0.047)	(0.047)	(0.047)	(0.047)	(0.079)	(0.069)
Cash × Post-pay × Higher wealth					−0.284**	−0.190**
					(0.144)	(0.093)
Cash × Announcement period	−0.002	0.014	0.014	0.012	0.013	0.039
	(0.035)	(0.035)	(0.035)	(0.035)	(0.072)	(0.061)
Cash × Announcement period × Higher wealth					0.013	−0.039
					(0.135)	(0.081)
Linear baseline output	Y	Y	Y	Y	Y	Y
Quadratic baseline output	N	Y	Y	Y	Y	Y
Post-double selection lasso controls	N	N	Y	Y	Y	Y
Day FE and hour FE	N	N	N	Y	N	N
Round-wave FE	Y	Y	Y	Y	Y	Y
p-value Cash × Post-pay = Cash × Announcement period	.006	.008	.008	.007	.000	.000
Wealth index					Continuous	Binary
Coeff.: Cash × Post-pay + Cash × Post-pay × Wealth					−0.064	0.014
Std. err.: Cash × Post-pay + Cash × Post-pay × Wealth					0.093	0.063
p-value: Cash × Post-pay + Cash × Post-pay × Wealth					.489	.819
N: worker-hours	17,441	17,441	17,441	17,441	17,381	17,381

Table III 展示了宣告临时工资发放计划以及实际临时工资发放对工人生产率的影响，第 3 列展示了基准模型（1）的回归结果，结果表明：单纯宣告临时工资发放计划对工人生产率没有显著影响，只有在实际发放临时工资后，工人生产率才出现了显著提升。此外，第 5、6 列通过在模型中加入工人财富水平高低的虚拟变量，进一步控制工人在实验前的财富水平进行回归，结果发现：临时工资发放对生产率的提高效应在较穷的工人中更加显著。

E. 实证结果 3：对工作时注意力（Attentiveness at Work）的影响

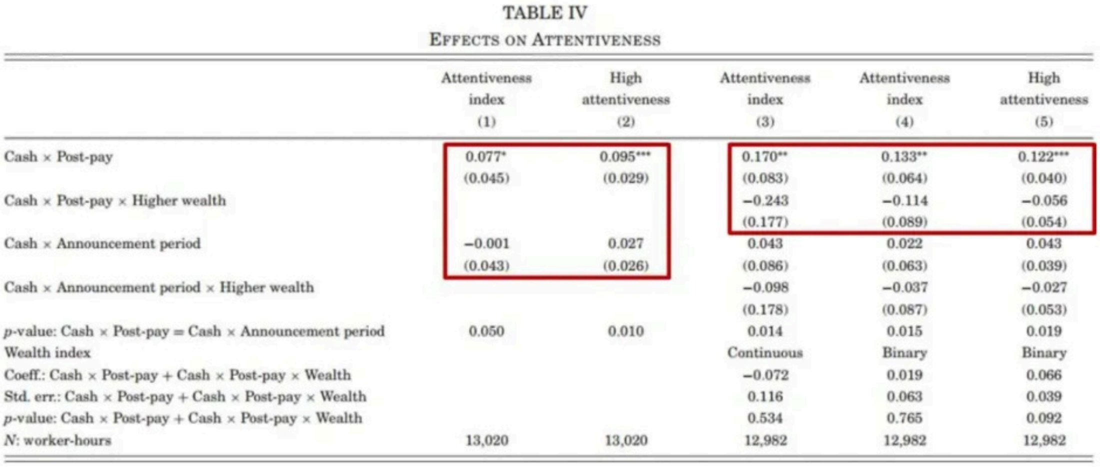


TABLE IV

EFFECTS ON ATTENTIVENESS

	Attentiveness index (1)	High attentiveness (2)	Attentiveness index (3)	Attentiveness index (4)	High attentiveness (5)
Cash × Post-pay	0.077*	0.095***	0.170**	0.133**	0.122***
	(0.045)	(0.029)	(0.083)	(0.064)	(0.040)
Cash × Post-pay × Higher wealth			−0.243	−0.114	−0.056
			(0.177)	(0.089)	(0.054)
Cash × Announcement period	−0.001	0.027	0.043	0.022	0.043
	(0.043)	(0.026)	(0.086)	(0.063)	(0.039)
Cash × Announcement period × Higher wealth			−0.098	−0.037	−0.027
			(0.178)	(0.087)	(0.053)
p-value: Cash × Post-pay = Cash × Announcement period	0.050	0.010	0.014	0.015	0.019
Wealth index			Continuous	Binary	Binary
Coeff.: Cash × Post-pay + Cash × Post-pay × Wealth			−0.072	0.019	0.066
Std. err.: Cash × Post-pay + Cash × Post-pay × Wealth			0.116	0.063	0.039
p-value: Cash × Post-pay + Cash × Post-pay × Wealth			0.534	0.765	0.092
N: worker-hours	13,020	13,020	12,982	12,982	12,982

Table IV 展示了宣告临时工资发放计划以及实际临时工资发放对工人工作时注意力的影响。估计结果表明：（1）第 1 列和第 2 列结果表明单纯宣告临时工资发放计划对工人工作时注意力没有显著影响，只有在实际发放临时工资后，工人工作时的注意力才出现了显著提升；（2）第 3、4、5 列估计表明临时工资发放对工人工作时注意力的提高效应在较穷的工人中更加显著。总之，这些结果表明，实验观察到的工人生产率在临时工资发放之后有所提高，这一改变至少部分是通过临时工资发放提升工人工作时的注意力来实现的。

F. 实证结果 4：计件工资变化（Piece Rate）的补充实验

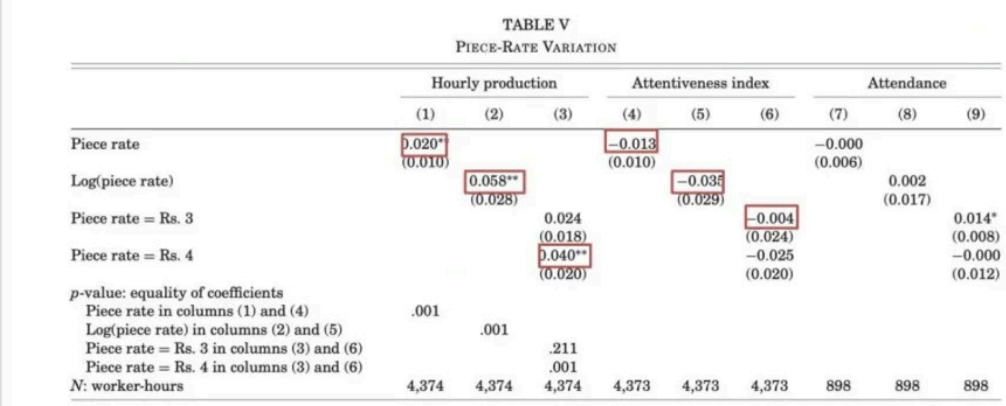


TABLE V

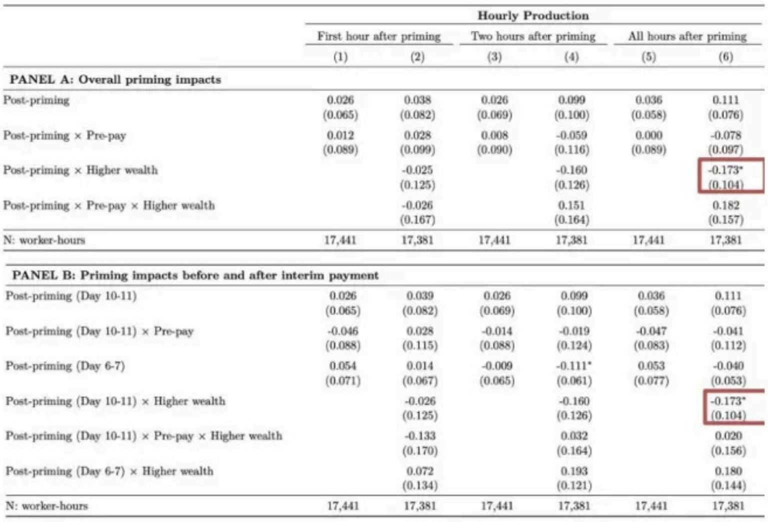
PIECE-RATE VARIATION

	Hourly production			Attentiveness index			Attendance		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Piece rate	0.020*			−0.013			−0.000		
	(0.010)			(0.010)			(0.006)		
Log(piece rate)		0.058**			−0.035			0.002	
		(0.028)			(0.029)			(0.017)	
Piece rate = Rs. 3			0.024			−0.004			0.014*
			(0.018)			(0.024)			(0.008)
Piece rate = Rs. 4			0.040**			−0.025			−0.000
			(0.020)			(0.020)			(0.012)
p-value: equality of coefficients									
Piece rate in columns (1) and (4)	.001								
Log(piece rate) in columns (2) and (5)		.001							
Piece rate = Rs. 3 in columns (3) and (6)			.211						
Piece rate = Rs. 4 in columns (3) and (6)			.001						
N: worker-hours	4,374	4,374	4,374	4,373	4,373	4,373	898	898	898

临时支付提高了工人的生产力和专注度。那么，这是否仅仅是因为工人变得更加有动力?为了探寻努力效应的影响，作者进行了计件工资变化的补充实验。通过 Table V 结果可知，计件工资变动影响产出结果（Hourly production），但对专注度（Attentiveness index）无明显影响，因此工人更加努力工作时，生产力提高，但专注度不会增加。

G. 实证结果 5：启动效应（Priming）的补充实验

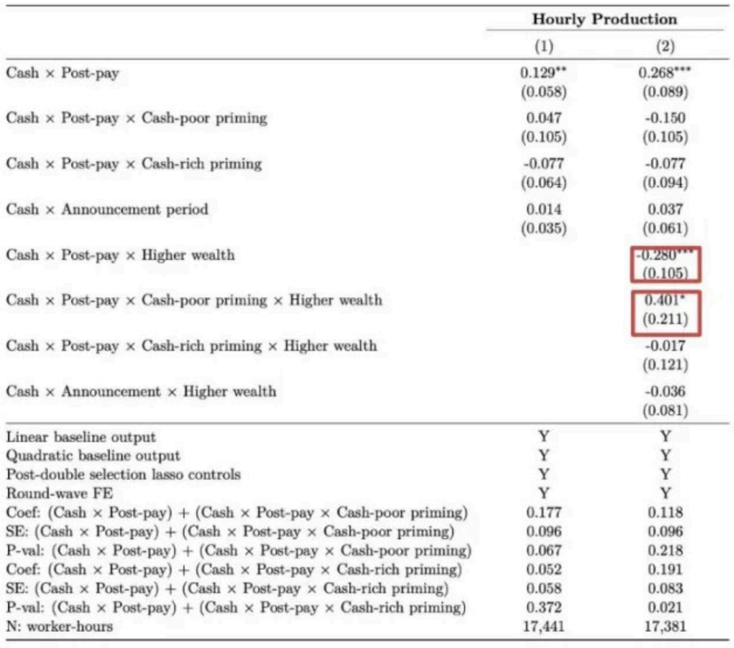
Table A.14: Effects of Priming



	Hourly Production					
	First hour after priming		Two hours after priming		All hours after priming	
	(1)	(2)	(3)	(4)	(5)	(6)
PANEL A: Overall priming impacts						
Post-priming	0.026 (0.065)	0.038 (0.082)	0.026 (0.069)	0.099 (0.100)	0.036 (0.058)	0.111 (0.076)
Post-priming × Pre-pay	0.012 (0.089)	0.028 (0.099)	0.008 (0.090)	-0.059 (0.116)	0.000 (0.089)	-0.078 (0.097)
Post-priming × Higher wealth		-0.025 (0.125)		-0.160 (0.126)		-0.173* (0.104)
Post-priming × Pre-pay × Higher wealth		-0.026 (0.167)		0.151 (0.164)		0.182 (0.157)
N: worker-hours	17,441	17,381	17,441	17,381	17,441	17,381
PANEL B: Priming impacts before and after interim payment						
Post-priming (Day 10-11)	0.026 (0.065)	0.039 (0.082)	0.026 (0.069)	0.099 (0.100)	0.036 (0.058)	0.111 (0.076)
Post-priming (Day 10-11) × Pre-pay	-0.046 (0.088)	0.028 (0.115)	-0.014 (0.088)	-0.019 (0.124)	-0.047 (0.083)	-0.041 (0.112)
Post-priming (Day 6-7)	0.054 (0.071)	0.014 (0.067)	-0.009 (0.065)	-0.111* (0.061)	0.053 (0.077)	-0.040 (0.053)
Post-priming (Day 10-11) × Higher wealth		-0.026 (0.125)		-0.160 (0.126)		-0.173* (0.104)
Post-priming (Day 10-11) × Pre-pay × Higher wealth		-0.133 (0.170)		0.032 (0.164)		0.020 (0.156)
Post-priming (Day 6-7) × Higher wealth		0.072 (0.134)		0.193 (0.121)		0.180 (0.144)
N: worker-hours	17,441	17,381	17,441	17,381	17,441	17,381

在某个随机选择的日子里，我们询问工人他们会如何筹集资金来应对突如其来的大额开支。我们提出了竞争性假设：将经济担忧置于首位可能通过认知效应降低产出；提醒工人其财务需求可能激励他们更努力工作或集中注意力，从而提高产出。 Table A.14 展示了启动干预结果，无论是整体样本还是支付前后两天在接受启动干预后一两个小时内几乎无效，启动后一整天对单小时产量的提升效果甚微。

Table A.15: Effects of Cash across Priming Conditions



	Hourly Production	
	(1)	(2)
Cash × Post-pay	0.129** (0.058)	0.268*** (0.089)
Cash × Post-pay × Cash-poor priming	0.047 (0.105)	-0.150 (0.105)
Cash × Post-pay × Cash-rich priming	-0.077 (0.064)	-0.077 (0.094)
Cash × Announcement period	0.014 (0.035)	0.037 (0.061)
Cash × Post-pay × Higher wealth		-0.280*** (0.105)
Cash × Post-pay × Cash-poor priming × Higher wealth		0.401* (0.211)
Cash × Post-pay × Cash-rich priming × Higher wealth		-0.017 (0.121)
Cash × Announcement × Higher wealth		-0.036 (0.081)
Linear baseline output	Y	Y
Quadratic baseline output	Y	Y
Post-double selection lasso controls	Y	Y
Round-wave FE	Y	Y
Coef: (Cash × Post-pay) + (Cash × Post-pay × Cash-poor priming)	0.177	0.118
SE: (Cash × Post-pay) + (Cash × Post-pay × Cash-poor priming)	0.096	0.096
P-val: (Cash × Post-pay) + (Cash × Post-pay × Cash-poor priming)	0.067	0.218
Coef: (Cash × Post-pay) + (Cash × Post-pay × Cash-rich priming)	0.052	0.191
SE: (Cash × Post-pay) + (Cash × Post-pay × Cash-rich priming)	0.058	0.083
P-val: (Cash × Post-pay) + (Cash × Post-pay × Cash-rich priming)	0.372	0.021
N: worker-hours	17,441	17,381

Table A.15 展示了不同人群在接受启动效应后的产量变化结果。从结果可得，对于“现金不足”的相对富人来说，产量得以降低，但是给予启动效应后，单位产量增加。我们认为引导工人关注财务状况可增强工作动力

V. 混淆因素和补充测试

在研究中，作者考虑了可能影响结果的多种混淆因素，并进行了补充测试以

确保结果的稳健性。以下是主要的分析和发现：

A. 公平与信任的影响

公平感的潜在影响：作者首先探讨了工人是否可能因为提前支付而产生公平感或礼物交换效应。例如，接受提前支付的工人可能因为感到被“优待”而更加努力工作（礼物交换效应），而未接受提前支付的工人可能因为感到不公平而减少努力（公平感效应）。

TABLE VI 显示，未发现任何证据表明公告期间的生产力发生变化。即使在支付安排宣布后，控制组工人的生产力也没有显著下降。在公告后的第一天和第二天，处理组和控制组的生产力差异不显著，作者还测试了控制组工人是否在看到处理组工人提前支付后减少努力，但未发现显著影响。支付后的显著效应表明，生产力提升仅与资金注入相关。说明资金注入是主因，控制组未因他人支付而改变行为，排除公平性干扰。

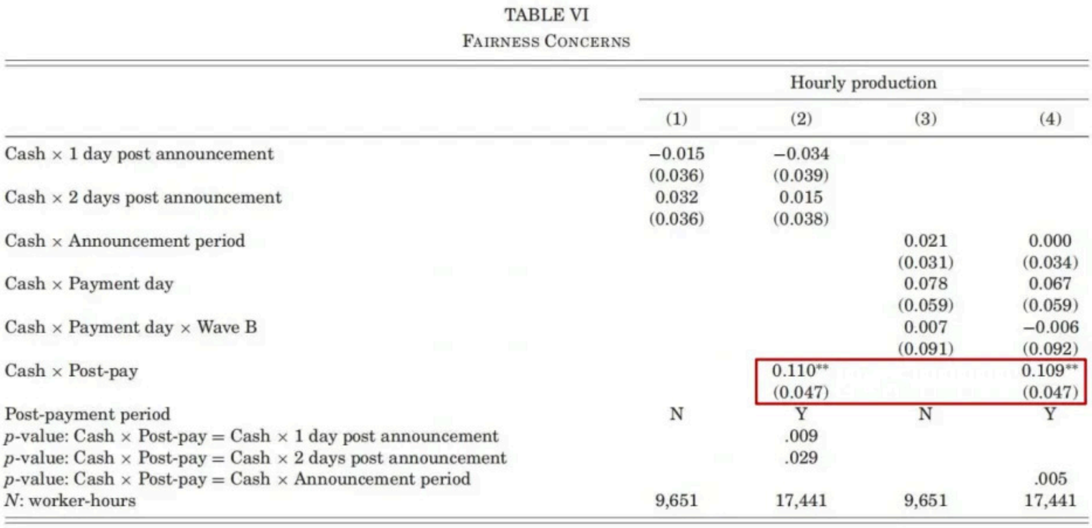


TABLE VI
FAIRNESS CONCERNS

	Hourly production			
	(1)	(2)	(3)	(4)
Cash × 1 day post announcement	−0.015	−0.034		
	(0.036)	(0.039)		
Cash × 2 days post announcement	0.032	0.015		
	(0.036)	(0.038)		
Cash × Announcement period			0.021	0.000
			(0.031)	(0.034)
Cash × Payment day			0.078	0.067
			(0.059)	(0.059)
Cash × Payment day × Wave B			0.007	−0.006
			(0.091)	(0.092)
Cash × Post-pay		0.110^{**}		0.109^{**}
		(0.047)		(0.047)
Post-payment period	N	Y	N	Y
p-value: Cash × Post-pay = Cash × 1 day post announcement		.009		
p-value: Cash × Post-pay = Cash × 2 days post announcement		.029		
p-value: Cash × Post-pay = Cash × Announcement period				.005
N: worker-hours	9,651	17,441	9,651	17,441

信任的潜在影响：提前支付可能通过增强工人对未来支付的信任感而提高生产力，信任可能因支付承诺兑现而扩散至控制组。作者通过以下方式测试这一假设：

在实验中，所有工人在第一天都按时收到支付，以建立信任。TABLE VI 显示，Wave B 处理组在第 9 天支付时，控制组的生产力未因观察到 Wave A 支付而变化，排除了信任扩散的可能性。信任效应无法解释生产力的提升，因为信任效应应与生产力的提升同时发生，但显示生产力的提升仅在工人实际收到支付后才出现。Table A.16 显示信任水平与处理效应无关，进一步排除了信任机制。

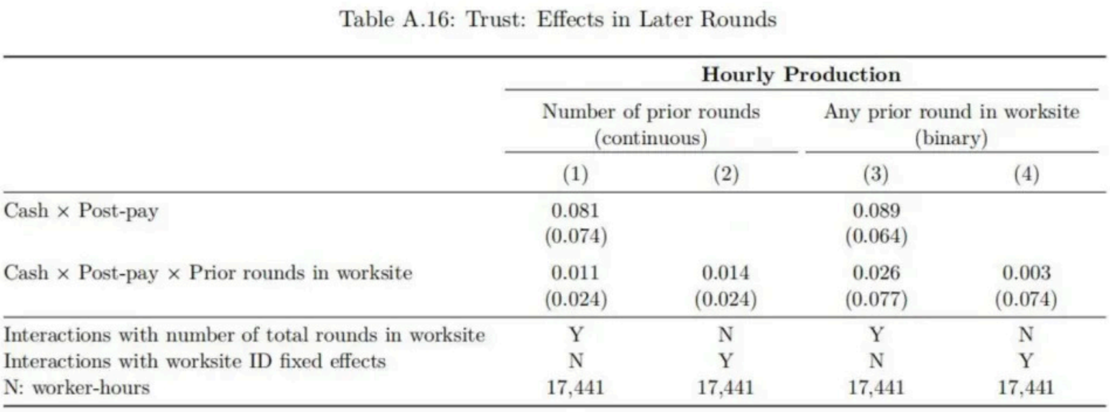


Table A.16: Trust: Effects in Later Rounds

	Hourly Production			
	Number of prior rounds (continuous)		Any prior round in worksite (binary)	
	(1)	(2)	(3)	(4)
Cash × Post-pay	0.081 (0.074)		0.089 (0.064)	
Cash × Post-pay × Prior rounds in worksite	0.011 (0.024)	0.014 (0.024)	0.026 (0.077)	0.003 (0.074)
Interactions with number of total rounds in worksite	Y	N	Y	N
Interactions with worksite ID fixed effects	N	Y	N	Y
N: worker-hours	17,441	17,441	17,441	17,441

B. 生理渠道：营养与睡眠的影响

营养的潜在影响：作者探讨了提前支付是否通过改善工人的营养状况而提高生产力。生物和医学文献表明，营养状况的改善通常不会在短时间内产生显著影响。因此，作者测试了工人是否因为早餐摄入增加而导致血糖波动，从而提高生产力。TABLE VII 显示，两组工人在早餐摄入量上没有显著差异，且生产力的提升在整个工作日中持续存在，排除营养效应干扰。

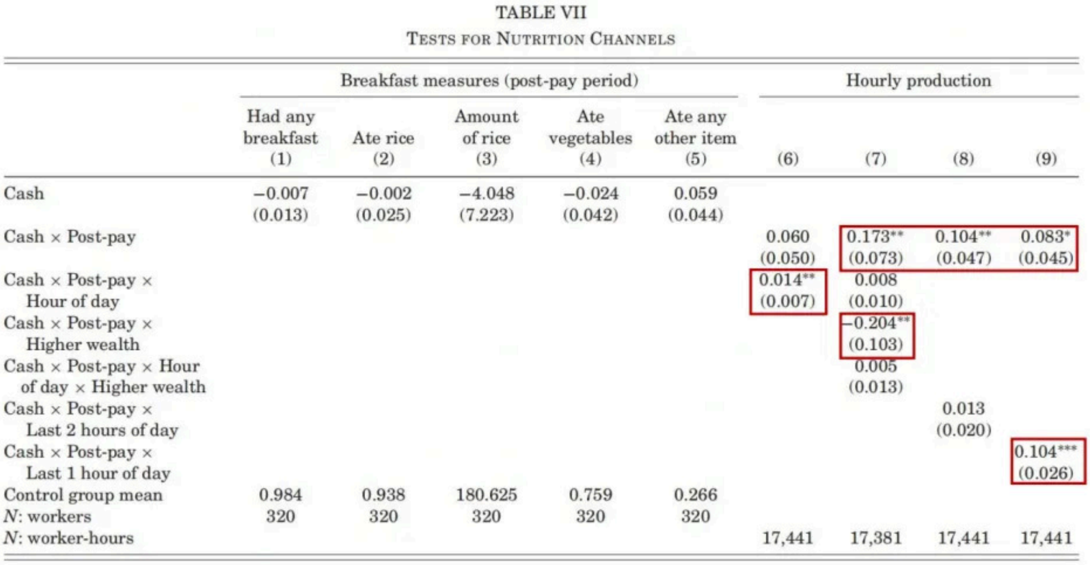


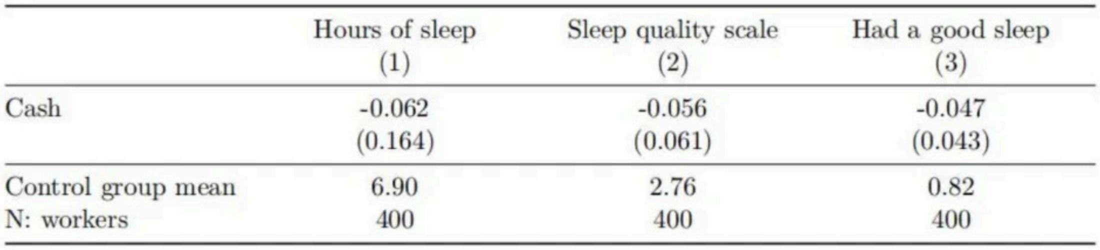
TABLE VII

Tests for Nutrition Channels

	Breakfast measures (post-pay period)					Hourly production			
	Had any breakfast (1)	Ate rice (2)	Amount of rice (3)	Ate vegetables (4)	Ate any other item (5)	(6)	(7)	(8)	(9)
Cash	−0.007 (0.013)	−0.002 (0.025)	−4.048 (7.223)	−0.024 (0.042)	0.059 (0.044)				
Cash × Post-pay						0.060 (0.050)	0.173** (0.073)	0.104** (0.047)	0.083* (0.045)
Cash × Post-pay × Hour of day						0.014** (0.007)	0.008 (0.010)		
Cash × Post-pay × Higher wealth							−0.204** (0.103)		
Cash × Post-pay × Hour of day × Higher wealth							0.005 (0.013)		
Cash × Post-pay × Last 2 hours of day								0.013 (0.020)	
Cash × Post-pay × Last 1 hour of day									0.104*** (0.026)
Control group mean	0.984	0.938	180.625	0.759	0.266				
N: workers	320	320	320	320	320				
N: worker-hours						17,441	17,381	17,441	17,441

睡眠的潜在影响：作者还测试了提前支付是否通过改善睡眠质量而提高生产力。Table A.17 显示，控制组工人报告的睡眠时间和质量未有显著变化，睡眠改善对生产力的影响有限。排除睡眠干扰。

Table A.17: Effects on Reported Sleep Quantity and Quality



	Hours of sleep (1)	Sleep quality scale (2)	Had a good sleep (3)
Cash	-0.062 (0.164)	-0.056 (0.061)	-0.047 (0.043)
Control group mean	6.90	2.76	0.82
N: workers	400	400	400

VI.结论

“财务担忧是否使工人生产力下降？”这项研究通过观察低收入印度计件制造工人的样本，测试了减少财务担忧是否会提高生产力的假设。研究发现，通过提前支付工资给一些工人提供现金注入，而其他工人则继续保持流动性约束，那些获得现金注入的工人会立即偿还债务并购买家庭必需品，从而减少了他们的财务担忧。随后，这些工人在工作中变得更加高效：他们的产出增加了 7%（0.11 标准差），并且他们犯的无意错误也更少了。手头有更多现金的工人不仅工作速度更快，而且更加专注，这表明了认知能力的提升。这些效应主要集中在财务更为受限的工人中。作者的研究结果还显示，在宣布期间并未检测到对注意力的影响；只有当钱真正到达工人手中后，注意力才有所改善。这些结果表明，尽管处于资金充裕的状态时，较贫穷的工人能够更好地规划和执行任务，导致需要撤销或修补的错误减少。

作者并没有具体说明引起观察到的生产力变化的具体心理机制（如担忧、焦虑或情感）。作者的实验旨在检验工人在工作时是否注意力不集中，而不是要区分导致这种注意力下降的确切心理原因——主要是因为无论确切的心理学原理是什么，许多经济影响都是相同的。相反，作者的目标是提供一个清晰的概念验证，即在高风险环境中，工人的行为决定了他们的收入，生产力效应是否会发生。作者发现，相对简单的财务压力调整就能对生产力产生有意义的影响。作者的研究结果幅度提示，进一步研究更广泛的干预措施（例如不同的薪酬结构或消费平滑技术）对于生产力的影响是一个有趣的方向。此外，作者的研究结果排除了公平、信任、营养和其他因素作为解释笔者结果的可能性，并指出财务紧张至少通过心理渠道有可能在最需要金钱的时候降低收入。

小组成员与老师合影

02

农业

AGRONOMICS

“双碳”目标下数字技术赋能农业碳生产率的影响

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摘要：在“双碳”目标下提升农业碳生产率对于缓解全球气候变化具有重要意义，而数字技术发展为农业低碳转型和经济绿色发展提供了新动能。选取 2013～2023 年中国 30 个省份的面板数据，采用基于加速遗传算法的投影寻踪模型和排放系数法分别测算乡村数字技术和农业碳生产率发展水平，并运用面板固定效应模型和空间杜宾模型研究数字技术发展对农业碳生产率的影响。结果表明：①中国乡村数字技术发展出现由东向西梯度递减的空间分布格局，农业碳生产率在西南地区出现“高-高”集聚特征，二者均呈现逐年上升态势。②乡村数字技术发展对农业碳生产率的提升有显著作用。③异质性检验显示，数字技术对农业碳生产率的提升效果呈现“西部>中部>东部”和“粮食产销平衡区>粮食主产区>粮食主销区”。④数字技术发展对邻近地区农业碳生产率具有正向空间溢出效应，其中 300 km 为空间溢出效应的密集区半径，700 km 为溢出效应的边界半径。

关键词：数字技术；农业碳生产率；投影寻踪；空间杜宾模型；空间衰减边界

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Impact of Digital Technology on Agricultural Carbon Productivity Under the Dual-carbon Goal

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Abstract: Enhancing agricultural carbon productivity under the dual-carbon goal is important for mitigating global climate change, and the development of digital technology provides a new impetus for the low-carbon transformation of agriculture and the green development of the economy. Using the panel data of 30 provinces in China from 2013 to 2023, the projected tracer model based on the accelerated genetic algorithm and the emission coefficient method are used to measure the development levels of rural digital technology and agricultural carbon productivity, respectively, and the panel fixed effect model and spatial Durbin model are used to study the impact of digital technology development on agricultural carbon productivity. The results show that: ①the development of digital technology in China has a spatial distribution pattern of decreasing gradient from east to west, and the agricultural carbon productivity in the southwest region has a high-high clustering pattern, and both of them show an increasing trend year by year. ②The development of rural digital technology has a significant effect on the improvement of agricultural carbon productivity. ③The heterogeneity test shows that the effect of digital technology on the improvement of agricultural carbon productivity is “western > central > eastern” and “balanced grain production and marketing area > main grain production area > main grain marketing area”. ④The development of digital

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technology has a positive spatial spillover effect on agricultural carbon productivity in neighboring regions, with intensive spillovers within 300 km and detectable effects extending to 700 km of the spillover effect.

Key words: digital technology; agricultural carbon productivity; projection tracing; spatial Durbin model; spatial decay boundaries

面对全球气候变化日益加剧的形势，控制碳排放已成为各国追求可持续发展的核心任务[1]。随着极端气候事件频发和生态系统退化等环境问题凸显，推动绿色低碳转型显得尤为迫切。中国明确提出“碳达峰、碳中和”目标，旨在通过绿色低碳转型实现经济社会的高质量发展。农业作为国民经济的基础产业，在实现“双碳”目标中扮演着双重角色：既是重要的碳汇系统，通过植被固碳和土壤碳封存缓解气候变化；同时又是温室气体排放的主要源头[2]，其活动及导致的土地利用变化约占全球排放总量的 13%，成为了仅次于其他行业的第二大排放源[3]。聚焦我国农业发展实际，低碳转型面临多维挑战，农业生产效能未充分释放，农用资源投入强度过高与耕地细碎化分布形成叠加制约[4]，削弱了碳排放管控效能。在粮食安全战略红线约束下，农业生产仍依赖能源密集型和排放粗放型的传统路径，区域间发展梯度差异进一步加剧了低碳农业推进的结构性矛盾，形成绿色转型进程中的复合阻滞[5]。这种发展形态与现代农业低碳化、集约化和可持续化的转型诉求存在显著差异，亟待系统性破局[6]。数字技术的出现正在重塑这一格局，通过乡村数字技术与农业经济的深度融合，推动传统高碳农业生产模式向环境友好型发展方式转型[7]。精准农业技术和智能化设施等技术的应用可以实现农业资源优化，使生产环节绿色低碳，提升农业生产效率[8]，这一系统性变革既为农业环境可持续发展提供了技术支撑，更通过创新动能推动农业现代化。作为正处于发展中的农业大国，中国面临减少碳排放的艰巨任务。在此背景下，探索如何通过乡村数字技术降低农业碳排放，提高碳生产率并发展绿色农业经济，成为推进“碳达峰、碳中和”目标的关键议题。

针对农业碳生产率问题，根据目前研究可以从概念和测算方法进行综述。Kaya 等[9]最先提出碳生产率就是单位二氧化碳排放的 GDP 水平，反映单位二氧化碳排放所带来的经济效益。碳生产率从经济学角度看，是在一定的技术水平条件下，碳排放作为社会经济发展的一种投入要素和约束性指标，用最少的碳资源投入获得最大的产出[10]。随后，学者们在农业领域的碳生产率测算主要分为单要素碳生产率和全要素碳生产率。吴传清等[11]以资本、人员和能源为投入指标，GDP 为期望产出，二氧化碳为非期望产出测算中国全要素碳生产率。农业单要素碳生产率是用农业生产总值与农业碳排放总量比值表示，单要素生产率经济内涵清晰，便于比较，是目前学界运用最多且被广泛认可的测算方法[12]。

针对数字技术的研究，诸多学者开展了相应研究，根据已有研究可以从数字技术的概念、数字技术经济效应和环境效应这 3 个方面进行综述。von Briel 等[13]认为数字技术不仅包括信息通信技术本身，还包括通过这类技术生产的产品或提供的服务。在农业领域，乡村数字技术作为数字技术的具体应用形态，主要指服务于农业生产系统、农村经济活动和乡村治理体系的系统性技术集成。在数字技术的经济效应层面，数字技术建设为乡村振兴提供了有力支撑，已有研究证明数字经济能够促进农业经济增长[14]。数字技术在绿色农业的产前、产中和产后环节都具有广泛的应用[15]，以上技术能够支持农业经济发展、提升农民收入和促进农业结构转型等。在数字技术的环境效应层面，学者们发现数字技术通过产业结构高级化调整、提升能源利用率[16, 17]和提高创新水平[18]，能够显著降低碳排放[19]。此外，农业产业聚集一旦突破临界规模，乡村数字技术可以提升农业生态效率[20]。王凤婷等[21]研究发现农村数字化通过促进技术创新、规模经营、结构升级、产业集聚和非农就业，进而实现对农业全要素碳生产率的提升。刘颖等[22]利用空间计量模型研究发现数字乡村建设可以实现本地和邻地农业碳减排。

从梳理文献可知，学界普遍认为乡村数字技术对农业经济和农业碳排放具有重要影响，然而，在农业经济高质量发展和“双碳”的双重背景下，乡村数字技术与农业碳生产率关系的系统研究仍显不足。现有文献虽指出乡村数字技术能通过优化农业生产要素配置影响自然环境，但多聚焦于碳排放量或农业经济等单一层面，缺乏对农业经济发展与碳减排双重影响的综合考量，更未深入探讨两者关系的空间延展性。

基于此，本研究力求在以下方面做出边际贡献：①在乡村数字技术的测度上，采用基于加速遗传算法的投影寻踪模型代替主成分分析等传统方法，其赋权与测度结果更加全面客观。②分析乡村数字技术与农业碳生产率的时空演变特征，探究二者的空间分布格局和空间相关性。③借助面板固定效应模型，从农业碳生产率的角度讨论乡村数字技术的“降碳促经”双重效应，综合考虑区位条件和农业资源禀赋差异两方面，探讨降碳促经效应的异质性，填补相关研究视角的空白。④构建空间计量模型探究乡村数字技术对农业碳生产率的空间溢出效应和地理距离衰减特征，对现有研究的空间延展性进行补充。这一研究不仅弥补了数字技术环境效应研究的理论空白，还为我国农业实现“双碳”目标和推动绿色低碳转型提供了重要的理论依据和实践启示。

1 理论分析框架

1.1 数字技术对农业碳生产率的直接效应

近年来，数字技术从“嵌入”到“融入”生态环境治理，成为生态治理的内在要素，引领国家治理理念，推动生态治理现代化变革[23]。数字技术的迅猛发展为农业碳减排带来了新的契机和解决方案。数字技术通过促进数据沉淀、资源共享与创新协同，为科技驱动的碳减排提供底层支撑，并借助数字化平台实现创新要素的高效配置与优化整合[24]。数字技术作为多种新型信息技术融合交错的整合，凭借其强大的共享性、渗透力和边际收益递增的特性[25, 26]，在粮食生产、耕地保护以及工业技术等多个领域都展现出了显著的改进效果。白婉婷等[27]认为随着数字技术的飞速进步，现代农业技术如精准农业和智能农业的普及程度显著提高，加速了农业生产效率的优化进程。同时数字技术的应用可以促进资源使用的高效和绿色环保，从而提高农业碳生产率并促使农业绿色转型[28]，加速中国农业现代化进程。高鸣等[29]指出，数字技术与土地和资本等农业生产要素结合，在生产过程中农业生产过程高度机械化与智能化，实现精准施肥和灌溉，可以减少资源浪费；在运输过程中利用数字技术实现运输路径优化和流通能源消耗，从而减少农用资源和能源过量投入所引发的温室气体排放。数字技术不仅能够通过优化农业生产方式直接降低碳排放强度，还能通过延伸产业链和提升价值链打破农产品交易中的机会成本和地区限制，从而促进农业碳生产率的提升。基于此，提出假说 1：乡村数字技术发展可以促进农业碳生产率的提高。

1.2 数字技术对农业碳生产率的空间溢出效应

根据地理学第一定律，不同地区之间的相互联系可以促使数字技术发挥高渗透性、高协同性和高流动性，从而打破要素流动壁垒[30]，缩短空间距离，加强区域活动关联[31]，挖掘区域经济活动的广度与深度[32]。数字技术凭借其特有的技术属性，在极大程度上不仅直接增强了本地农业碳生产率，还对周边区域产生了正面的空间外溢效应。一方面，数字技术通过优化农业生产要素在不同地理区域间的配置，加速了资本、先进技术和劳动力的有效流转[33]，从而提高了跨区域的农业生产效率，并间接促使碳排放强度得以降低。另一方面，数字技术的外溢效应和共享特性，使得邻近地区能够及时获取到最新的低碳环保技术成果及市场动态信息，进一步推动绿色农业技术的革新与产业结构的优化升级，通过技术扩散对农业全要素碳生产率产生正向空间溢出效应[21]。基于以上论述，提出假说 2：乡村数字技术发展对农业碳生产率存在正向空间溢出效应。

1.3 数字技术对农业碳生产率的空间溢出效应距离衰减特征

在数字技术的发展过程中，人才的流动、知识的传播以及技术的创新对农业碳生产率的

空间溢出效应起到了重要作用[34, 35]。然而，这种空间溢出效应具有明显的地理局限性，尤其是在较小空间尺度下更为显著。相邻地区由于农业生产结构与自然资源条件相似，为了提升竞争力和实现协同发展，通常会加强合作与经济往来，从而促进生产要素的频繁自由流动[36]。然而，随着地区间地理距离的增加，农业生产要素的流动性逐渐减弱，知识与技术的溢出效果也随之递减。当地区间距离超过一定临界值时，高昂的交通成本会显著阻碍人才的流动，从而限制数字技术的空间溢出效应[37]。在这种情况下，数字技术对远距离地区农业碳生产率的影响相对有限[38]。据此，提出假说 3：乡村数字技术发展对农业碳生产率的空间溢出效应存在距离衰减特征。

2 材料与方法

2.1 模型设定

2.1.1 基于加速遗传算法的投影寻踪模型

对于乡村数字技术水平的评价，本文采用投影寻踪法，它是处理高维数据的技术，通过将数据投影到低维空间，并寻找最优投影方向来捕捉数据的核心特征。这种方法稳健、抗干扰且准确，尤其适用于解决复杂的非线性优化问题，克服了传统优化手段的局限[39]。本文参考王思薇等[40]的研究方法，引入加速遗传算法，高效地解决高维空间的全局优化难题。具体步骤如下。

（1） 数据归一化 设指标值$\{x^*(u, v) \mid u=1, 2, \dots, m; v=1, 2, \dots, n\}$，其中 $x(u, v)$为第 u 个地区的第 v 个指标；

$$\text{正向指标：}\ x(u,v)=\frac{x^*(u,v)-x_{\min}(v)}{x_{\max}(v)-x_{\min}(v)} \tag{1}$$

$$\text{负向指标：}\ x(u,v)=\frac{x_{\max}(v)-x^*(u,v)}{x_{\max}(v)-x_{\min}(v)} \tag{2}$$

式中，$x_{\max(v)}$和 $x_{\min(v)}$为第 v 个指标的最大值和最小值。

（2） 构造投影目标函数 假设 $c=\{c(1), c(2), \dots, c(n)\}$是投影方向，则样本 u 的投影值 $g(u)$ 公式为：

$$g(u)=\sum\nolimits_{j=1}^{n} c(v)\times(u,v),(u=1,2,\dots,m) \tag{3}$$

投影目标函数定义为 $Q(c)$，S_g 为类间距离，D_g 为类内密度，公式为：

$$Q(c)=S_g D_g \tag{4}$$

$$S_g=\sqrt{\frac{\sum\nolimits_{i=1}^{n}[g(u)-E(g)]^2}{m-1}} \tag{5}$$

$$D_g=\sum\nolimits_{u=1}^{m}\sum\nolimits_{v=1}^{m}[R-r(u,v)]\Box u[R-r(u,v)] \tag{6}$$

式中，$E(g)$ 为投影期望值，$r(u, v)$ 为单位跃迁函数，R 为窗宽参数。

（3） 依托加速遗传算法优化目标函数 随后，基于约束条件下使用加速遗传算法优化寻找最优投影方向 $Q(c)$。

$$\text{Max}:Q(c)=S_g D_g \tag{7}$$

$$\text{s.t.}\sum\nolimits_{j=1}^{n} c^2(j)=1 \tag{8}$$

（4） 指标赋权和测度 基于加速遗传算法的投影寻踪模型，利用 Matlab 设置参数后运行程序 1000 次后由降序排列得到最大的目标函数值，对应的最优投影方向即为指标权重，将指标权重代入式（3），即可得到 2013～2023 年乡村数字技术发展水平。

2.1.2 基准模型

为了分析乡村数字技术对农业碳生产率的影响，本文构建如下回归模型：

$$\mathrm{CP}_{it}=\alpha_0+\alpha_1\mathrm{DIG}_{it}+\sum\alpha_2X_{it}+\lambda_i+\mu_t+\varepsilon_{it} \tag{9}$$

式中，i 和 t 分别表示省份和年份，CP 表示农业碳生产率，DIG 表示乡村数字技术发展水平，X 表示控制变量，λ_i 和 μ_t 分别表示个体固定效应和时间固定效应，ε_{it} 表示随机扰动项。

2.1.3 空间计量模型

为了探讨乡村数字技术对农业碳生产率是否存在空间溢出效应，本文引入空间计量模型进行检验：

$$\mathrm{CP}_{it}=\theta_1+\rho\boldsymbol{W}\mathrm{CP}_{it}+\theta_2\mathrm{DIG}_{it}+\theta_3X_{it}+\beta_1\boldsymbol{W}\mathrm{DIG}_{it}+\beta_2\boldsymbol{W}X_{it}+\omega_i+\upsilon_t+\varepsilon_{it} \tag{10}$$

$$\varepsilon_{it}=\alpha\boldsymbol{W}\varepsilon_{it}+\gamma_{it} \tag{11}$$

式中，本文采用地理距离矩阵作为空间权重矩阵 $\boldsymbol{W}$。

为了进一步研究乡村数字技术空间溢出是否存在地理距离衰减现象。参考张益等[41]的研究，设定 100km 作为省级之间最短距离，以 100km 作为递进距离，矩阵设定为：

$$\boldsymbol{W}_{ij}=\begin{cases}\dfrac{1}{d_{ij}},d_{ij}\geq d\\ 0,d_{ij}<d\end{cases} \tag{12}$$

式中，d_{ij} 表示 i 和 j 省间距离，d 表示地理距离阈值。

2.2 变量说明

2.2.1 被解释变量：农业碳生产率（CP）

农业领域的碳生产率测算主要分为单要素碳生产率和全要素生产率。节能减排实践中所确立的各项目标，均聚焦于单要素碳生产率指标，而部分国际公约亦是在单要素框架下明确了减排的责任体系[12]。王倩等[42]认为，全要素碳生产率的增长，未必能切实反映出实际的减排成效。当运用全要素碳生产率对碳排放效率予以评估时，会因未能将其他要素中的非有效部分有效区分开来，进而致使评估结果出现偏差。因此，本文定义农业碳生产率为农业生产总值与其生产过程中所产生的碳排放量之比。测算公式为：

$$\mathrm{CP}=\frac{\mathrm{AGDP}}{C} \tag{13}$$

$$C=\sum C_i=\sum T_i\times\mathrm{CF}_i \tag{14}$$

式中，CP 表示农业碳生产率，AGDP 表示农业生产总值，C 表示农业碳排放总量，C_i 表示各类碳源碳排放量，T_i 表示各类碳源量，CF_i 表示第 i 种碳源的碳排放系数。

农业碳排放主要源自两大方面。其一，农业生产环节中各类农资的投入，包括农药、化肥、农膜、农用柴油以及灌溉用电，均会引发直接或间接的碳排放。并且，农业翻耕活动对土壤有机碳库的扰动，亦会导致碳排放的产生。其二，水稻生长过程中会产生甲烷（CH_4）排放。考虑到避免重复计算，稻田 CH_4 排放系数已被纳入化肥施用的影响体系之中。因此，在本研究的农业碳排放测算过程中，参考丁宝根等[43]的做法，农业碳排放量采用农药、化肥、农膜、农用柴油、灌溉以及土壤翻耕这六种碳源作为计算依据，具体碳排放系数如表 1 所示。

表 1 农业碳排放源、碳排放系数及相关数据来源

Table 1 Sources of agricultural carbon emissions, carbon emission factors and related data sources

碳源	碳排放系数	来源
柴油	0.59 kg·kg^{-1}	IPCC
化肥	0.89 kg·kg^{-1}	美国橡树岭国家实验室
农药	4.93 kg·kg^{-1}	美国橡树岭国家实验室
农膜	5.18 kg·kg^{-1}	南京农业大学农业资源与生态环境研究所
灌溉	266.48 kg·hm^{-2}	文献[44]
翻耕	312.60 kg·km^{-2}	文献[45]

2.2.2 核心解释变量：乡村数字技术水平（DIG）

由于数字技术无法孤立存在，当前对其发展水平的测度主要依赖于对承载数字技术的载体及其衍生效益的间接评估。从本质上讲，数字经济是由数字技术的应用所催生的经济产出[46]。基于此，对乡村数字技术发展水平的测度，本文参考苏群等[26]、朱红根等[47]和李燕凌等[48]的方法。依照“基础设施-经济动力-社会效益”的发展理论，从乡村数字设施、乡村产业数字化和乡村数字服务水平这 3 个维度构建乡村数字技术指标体系（见表 2）。

表 2 乡村数字技术发展评价指标体系 1)

Table 2 Indicator system for evaluating rural digital technology development

一级指标	二级指标	测度方法	单位	属性
乡村数字设施	农村互联网普及率	农村接入宽带用户/乡村人口	户·人$^{-1}$	+
	农村信息化设备	农村居民每百户计算机拥有量	台	+
		农村居民每百户移动电话拥有量	部	+
	农村气象观测服务	农业气象观测站数量	个	+
乡村产业数字化	农业电气化	农业机械总动力	万 kW	+
	农村运营数字化	农村电子商务销售额	亿元	+
		农村电子商务采购额	亿元	+
	农村数字产业创新基地	淘宝村数量	个	+
	农业生产投资	农林牧渔业固定资产投资	亿元	+
乡村数字服务水平	农村网络支付数量与规模	数字普惠金融指数	无量纲	+
	农村信息技术应用	农村邮政网点平均服务人口	万人	−
	数字产品与服务消费	农村居民数字产品和服务消费支出	元·人$^{-1}$	+
	农村流通数字化	农村投递路线	km	+

1) “+”表示该项指标为正向指标,数值越大越好,在后续处理过程中为正值，“−”表示该项指标为负向指标,数值越小越好,在后续处理过程中为负值

2.2.3 控制变量

参考现有关于农业碳生产率影响因素的研究，选取农业受灾情况、环境规制、农村居民收入和农户人力资本投资。其中，农业受灾情况（DIR）用受灾面积与农作物播种面积之比表示。环境规制（ER）以各省份环境保护支出与财政支出之比表示。农村居民收入（ICM）用农村居民人均可支配收入表示。农户人力资本投资（HI）用文教娱乐占总消费的比例表示。

2.2.4 数据说明

文章选取 2013～2023 年中国 30 个省份（中国台湾、香港、澳门和西藏资料暂缺），数据来源于《中国农村统计年鉴》《中国统计年鉴》《中国人口和就业统计年鉴》《中国淘宝村研究报告》及相关省（区、市）统计年鉴，数字普惠金融测度数据来源北京大学数字普惠金融指数[49]。部分缺失数据采用插值法补齐。各变量描述性统计分析如表 3 所示。

表 3 描述性统计

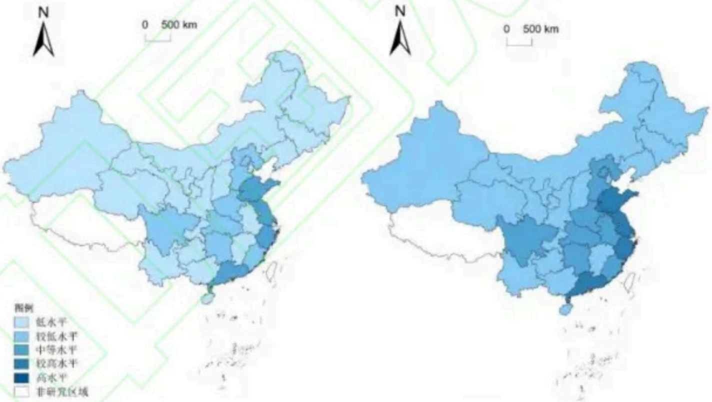
Table 3 Descriptive statistics

变量	样本	平均值	最小值	最大值	标准差
CP	330	7.105	2.509	27.106	3.414
DIG	330	0.979	0.342	2.292	0.366
DIR	330	0.122	0.001	0.695	0.107
ER	330	2.882	1.000	6.800	0.966
ICM	330	15.763	5.589	42.988	6.649
HI	330	10.091	4.300	14.800	2.279

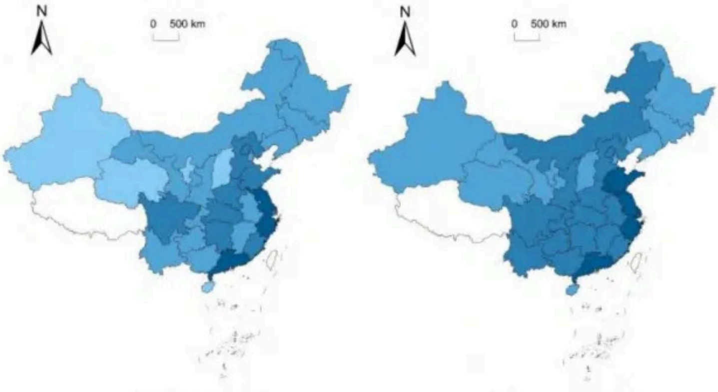
3 结果与分析

3.1 乡村数字技术与农业碳生产率空间演进特征

为更直观地分析乡村数字技术水平与农业碳生产率的时空演变特征，本文基于 ArcGIS 软件绘制了 2013 年、2017 年、2020 年和 2023 年的空间分布（图 1 和图 2）。从图 1 可以看出，我国乡村数字技术水平表现出显著的空间异质性。东部沿海地区（如山东、浙江和江苏）始终处于高水平，且随时间推移，“高-高”集聚特征愈发显著。西部地区乡村数字技术水平虽显著提升，但与东部地区相比仍存在一定差距，整体呈现由东向西梯度递减的空间分布格局。此外，中等水平和基础水平的区域逐渐向内陆延伸，表明乡村数字技术的普及和应用范围持续扩大，但区域间发展不平衡问题依然存在。从图 2 可以看出，农业碳生产率在西南地区呈现显著的“高-高”集聚特征，而中国北部地区则持续处于低位且波动较小。四川和贵州等地的农业碳生产率始终处于领先地位，与此同时，以上地区的乡村数字技术水平也较高，表明乡村数字技术与农业碳生产率存在一定的空间相关性。



(a) 2013年乡村数字技术水平　　(b) 2017年乡村数字技术水平

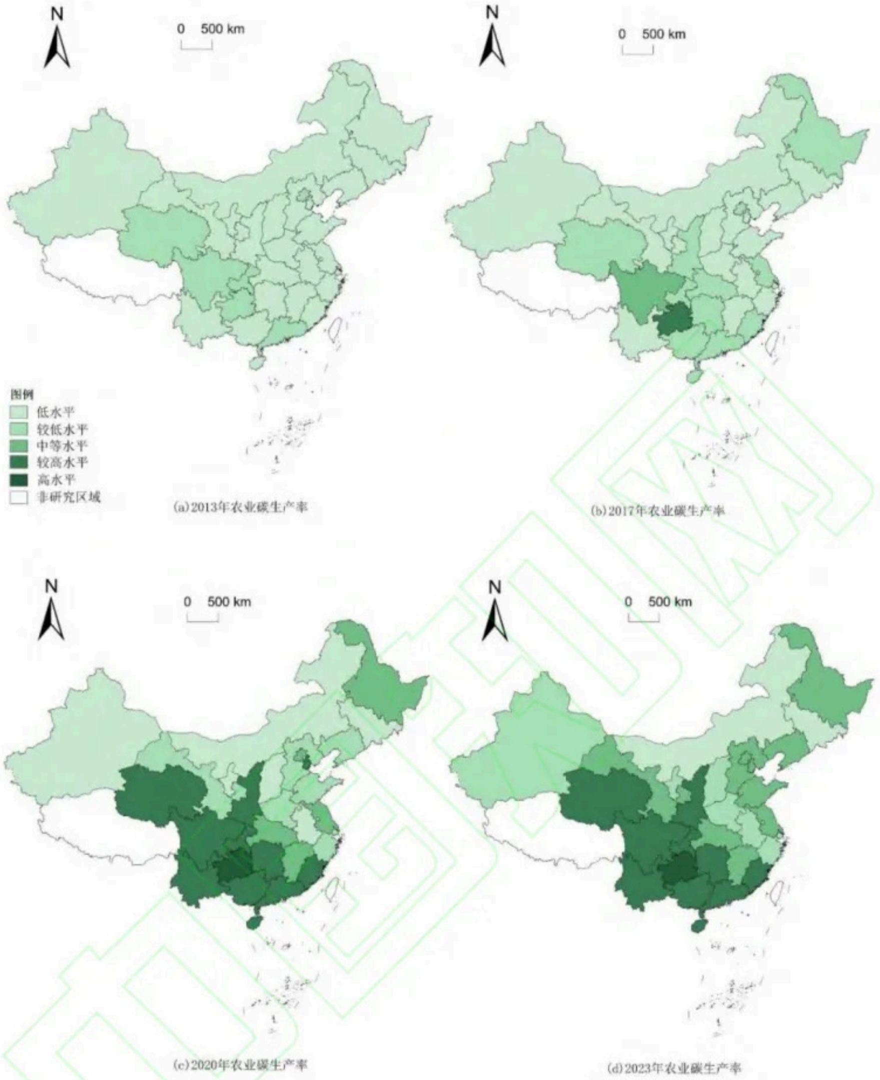


(c) 2020年乡村数字技术水平　　(d) 2023年乡村数字技术水平

基于自然资源部标准地图服务网站 GS(2024)0650 号的标准地图制作，底图边界无修改，下同

图 1 2013～2023 年乡村数字技术水平空间演变

Fig.1 Spatial evolution of rural digital technology levels from 2013 to 2023



(a) 2013年农业碳生产率

(b) 2017年农业碳生产率

(c) 2020年农业碳生产率

(d) 2023年农业碳生产率

图 2 2013～2023 年农业碳生产率空间演变

Fig.2 Spatial evolution of carbon productivity in agriculture from 2013 to 2023

3.2 乡村数字技术与农业碳生产率动态特征

本文利用 Matlab 绘制乡村数字技术水平与农业碳生产率的三维核密度图，进一步研究二者的动态特征。由图 3（a）可知，乡村数字技术水平分布曲线的主峰整体呈右移态势，表明各省份的乡村数字技术水平呈现不断上升趋势；从分布态势看，主峰高度降低反映了乡村数字技术水平的区域分布趋于均衡，表明技术扩散效应逐渐增强，区域间发展差距缩小。从极化趋势看，主峰旁存在侧峰，侧峰的出现则表明技术扩散在局部区域形成了多个高密度中心，反映了技术扩散的多极化和区域均衡化并存的特征。由图 3（b）可知，农业碳生产率核密度曲线波峰整体呈现右移态势，表明各地区农业碳生产率逐年上升；随着时间推移，主峰高度降低，波峰宽度增大，表明农业碳生产率的区域间差异缩小，表明不同区域的碳生产率水平趋于均衡发展。

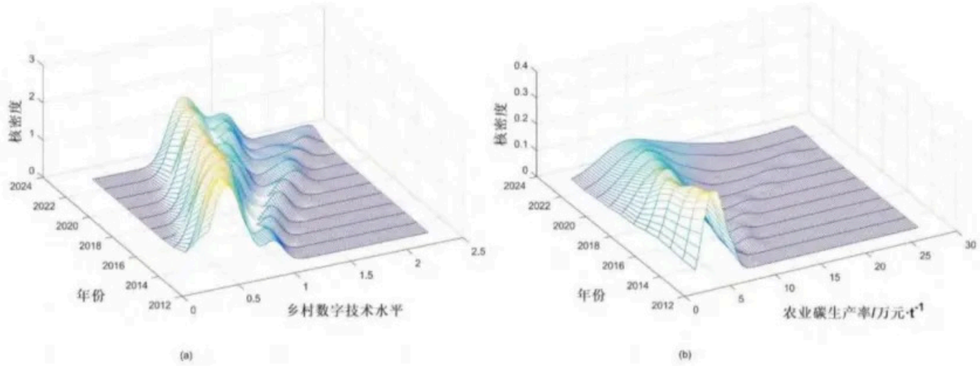


图 3 乡村数字技术与农业碳生产率核密度分布

Fig.3 Kernel density distribution of rural digital technologies and agricultural carbon productivity

3.3 基准回归结果分析

表 4 报告了双向固定面板模型的回归结果，列（1）～（4）分别表示逐步增加个体固定效应、年份固定效应与控制变量的结果，R^2 逐渐增加至 0.89，说明增加控制变量、年份和个体固定效应后的模型更能准确反映乡村数字技术对农业碳生产率的影响方向和大小。列（4）结果表明，乡村数字技术水平对农业碳生产率的影响系数在 1%的显著性水平下为 8.209，说明乡村数字技术发展可以显著促进农业碳生产率提升，本文假设 1 得证。原因在于，乡村数字技术改变了农业生产要素的结构，提高资源使用效率，减少由于资源浪费所引起的农业碳排放，提高农业碳生产率。

表 4 基准回归结果 1)

Table 4 Benchmark regression results

变量	CP			
	(1)	(2)	(3)	(4)
DIG	3.886***	6.906***	2.509**	8.209***
	(0.387)	(0.395)	(1.116)	(1.408)
DIR	—	—	—	0.242
	—	—	—	(0.924)
ER	—	—	—	16.034
	—	—	—	(10.080)
ICM	—	—	—	−0.549***
	—	—	—	(0.092)
HI	—	—	—	0.001
	—	—	—	(0.077)
Constant	3.301***	0.345	4.649***	7.212***
	(0.356)	(0.384)	(1.092)	(1.240)
个体固定效应	×	√	√	√
年份固定效应	×	×	√	√
N	330	330	330	330
R^2	0.17	0.83	0.86	0.89

1）** 和 *** 分别表示通过 5% 和 1% 水平下显著性检验，“—”表示该项目不涉及的变量，“√”表示模型中已控制该项固定效应，“×”表示模型中未控制该项固定效应，括号内数值为稳健标准误

3.4 稳健性检验

3.4.1 调整研究样本

考虑到 4 个直辖市存在特殊政策，并且基础发展条件都和其他地区存在明显差异，可能

会影响效应识别进而产生结果偏误。研究将剔除直辖市样本重新进行基准回归检验，结果如表 5 列（1）所示，核心解释变量（DIG）系数为 13.042，通过 1%的显著性检验，表明在剔除直辖市样本后，核心结论仍然稳健。

3.4.2 剔除异常值影响

为了减少极端值对估计结果的偏差，本研究将变量进行 1%和 99%分位点缩尾处理，将高于 99%分位点和低于 1%分位点的数值进行替换，然后重新进行基准回归分析，由表 5 列（2）结果可知，核心变量（DIG）均显著为正，这说明基准回归结果具有稳健性。

3.4.3 更换解释变量测度

基准回归中乡村数字技术水平采用基于遗传算法的投影寻踪模型进行测算，为验证结论稳健性，采用学术界更为普遍的熵值法对核心解释变量进行测算，表 5 列（3）回归系数仍然在 1%显著水平下为正，再次证明结果的稳健可靠。

3.4.4 增加控制变量

为了防止遗漏变量影响模型的估计结果，一方面，考虑到农业劳动生产率提升会促使产业结构调整和规模效应释放，新兴领域发展及规模化经营有利于实现碳减排与农业增加值提升，进而提高农业碳生产率。另一方面，农村受教育水平较高的农民更易接受和采用低碳农业技术，从而提高农业碳生产率。教育水平的提升能使农民更好地理解环保知识，增强低碳意识，有利于推动农业生产向低碳方向发展。因此，增加农业劳动生产率和农村受教育水平控制变量进行稳健性检验，表 5 列（4）结果表明，DIG 系数显著为正，再次说明乡村数字技术可以显著提升农业碳生产率。

3.4.5 内生性检验

考虑到乡村数字技术与农业碳生产率之间存在互为因果关系，为了减小内生性问题对乡村数字技术促进农业碳生产率的作用产生影响，本文将乡村数字技术发展水平滞后一期作为工具变量。两阶段回归结果如表 5 列（5）和列（6）所示，第一阶段结果表明工具变量对 DIG 具有显著正向影响，并且 F 统计值大于临界值 10，说明不存在弱工具变量问题。第二阶段结果表明 DIG 估计系数显著为正。因此，在进一步缓解内生性问题后，乡村数字技术发展对农业碳生产率提升具有显著作用。

表 5 稳健性检验 1)

Table5 Robustness test

变量	调整研究样本(1)	剔除异常值影响(2)	更换解释变量测度(3)	增加控制变量(4)	内生性检验	
					(5)	(6)
DIG	13.042***	6.869***	7.131***	5.837**	—	9.438***
	(2.018)	(1.122)	(1.853)	(2.369)	—	(3.609)
工具变量	—	—	—	—	0.844***	—
	—	—	—	—	（0.057）	—
*F*值	—	—	—	—	216.354	—
控制变量	√	√	√	√	√	√
个体固定效应	√	√	√	√	√	√
年份固定效应	√	√	√	√	√	√
N	286	330	330	330	330	330

1）** 和 *** 分别表示通过 5% 和 1% 水平下显著性检验，“—”表示该项目不涉及的变量，“√”表示模型中已控制该项固定效应，括号内数值为稳健标准误

3.5 异质性分析

一方面，不同地理位置的地区在数字基础设施建设的广度、数字化应用思想的深度以及地方政府所制定的支持政策等方面，均展现出显著的时空差异。另一方面，粮食种植水平也

是影响乡村数字化和农业碳排放量的关键因素。基于此，本文分别检验两类异质性。

3.5.1 区位条件

本文参考汪亚楠等[50]的划分思路将样本分为东部、中部和西部，结果如表 6 列（1）~（3）所示，乡村数字技术对中部和西部农业碳生产率在 1%显著性下显著，尤其是西部的回归系数（30.978）远大于中部与东部的回归系数。可能的原因在于，一方面，东部地区数字基础设施较为完善，且农业在经济中的比例较低，更多资源倾向于工业和服务业，导致数字技术在农业领域进一步推广的边际效应较小；而中西部地区数字基础设施相对薄弱，农业在经济中占比较高，数字技术的引入能够显著改善农业生产条件，从而产生更大的边际效应。另一方面，西部地区生态环境脆弱与资源禀赋较差，数字技术通过优化资源配置和提高资源利用效率，能够显著提升农业碳生产率；而东部地区农业现代化水平较高，数字技术的提升作用相对有限。因此，数字技术对中西部地区农业碳生产率的影响更为显著，尤其是在西部地区。

3.5.2 农业资源禀赋异质性

本文借鉴李成等[51]的研究思路，将样本划分为粮食主销区、粮食主产区和粮食产销平衡区，结果如表 6 列（4）~（6）所示，乡村数字技术在粮食主产区和粮食产销平衡区均能显著促进农业碳生产率提升。粮食主销区包括北京市、上海市和天津市等 7 个省级行政区，虽然其乡村数字技术基础较为发达，但是可能由于其耕地面积较小，尚未充分转化成为农业低碳生产力，故而数字技术的生态效应不佳。相比于粮食主产区，粮食产销平衡区乡村数字技术的降碳促经作用效果更优。可能的原因在于粮食产销平衡区农业生产类型更为多样化，经济作物和特色种植占比较高，这类农业生产活动通过数字技术实现精准化管理，如智能灌溉与精准施肥等的潜力更大，能更有效地提升资源利用效率并降低碳排放强度。产销平衡区农业经营规模通常较为适中，既不像主销区那样受限于耕地规模，也不像主产区那样面临大规模单一化种植的技术推广难题，使得数字技术的应用推广能够更好地适应其生产需求，创造降碳促经协同效应。

表 6 异质性分析 1)

Table 6 Heterogeneity analysis

变量	东部(1)	中部(2)	西部(3)	粮食主销区(4)	粮食主产区(5)	粮食产销平衡区(6)
DIG	1.196	4.414**	30.978***	0.447	7.324***	36.943***
	(1.052)	(1.691)	(4.414)	(0.718)	(1.837)	(5.553)
控制变量	√	√	√	√	√	√
个体固定效应	√	√	√	√	√	√
年份固定效应	√	√	√	√	√	√
Constant	13.834***	−2.666	−6.765	23.387***	4.147***	−12.420**
	(2.449)	(3.286)	(4.672)	(2.206)	(1.576)	(5.013)
N	121	88	121	77	143	110

1）** 和 *** 分别表示通过 5% 和 1% 水平下显著性检验，“√”表示模型中已控制该项固定效应，括号内数值为稳健标准误

3.6 空间溢出效应分析

3.6.1 空间自相关分析

本文基于 2013~2023 年 30 个省份的面板数据，分年度计算了乡村数字技术（DIG）和农业碳生产率（CP）的全局 Moran’s *I* 指数，结果如表 7 所示。首先，乡村数字技术的全局 Moran’s *I* 指数均显著为正，表明各省份之间的乡村数字技术存在显著的空间相关性。其次，农业碳生产率的 Moran’s *I* 指数在 2016 年之前为负但不显著，说明早期农业碳生产率发展尚不完善，区域间的空间关联性较弱；然而，2016 年之后，全局 Moran’s *I* 指数显著

为正，并逐年增大至 0.127，表明农业碳生产率在区域间呈现出不断增强的正向空间溢出效应。因此，有必要进一步做空间效应分析。

表 7 2013～2023 年全局 Moran's *I* 指数 1)

Table 7 Global Moran's *I* index from 2013 to 2023

年份	DIG		CP	
	全局 Moran's *I*	*P* 值	全局 Moran's *I*	*P* 值
2013	0.024	0.107	−0.059	0.492
2014	0.030	0.075*	−0.022	0.716
2015	0.032	0.066*	−0.007	0.412
2016	0.059	0.009***	0.042	0.025**
2017	0.040	0.038**	0.054	0.007***
2018	0.029	0.076*	0.081	0.000***
2019	0.037	0.045**	0.101	0.000***
2020	0.034	0.055*	0.103	0.000***
2021	0.054	0.013**	0.111	0.000***
2022	0.059	0.009***	0.109	0.000***
2023	0.070	0.003***	0.127	0.000***

1）*、** 和 *** 分别表示通过 10%、5% 和 1% 水平下显著性检验

3.6.2 模型选择

上述的空间自相关检验结果表明乡村数字技术（DIG）和农业碳生产率（CP）存在空相关性的，为选取合适的空间计量模型检验二者之间的空间效应，还需进行必要的检验。表 8 表明，LM 检验各统计量至少通过 10%显著性检验，说明存在空间误差和空间滞后效应。LR 检验表明在 1%显著性水平下 SDM 模型更优。Wald 检验表明 SDM 模型不会退化为 SAR 或 SEM 模型。时空-时间固定效应检验在 1%显著性水平下拒绝原假设，因此本文选择时空双固定的空间杜宾模型。

表 8 空间计量模型选择检验 1)

Table 8 Spatial measurement model selection test

检验方法		检验值	*P* 值
LM 检验	全局 Moran's *I*	10.974	0.000***
	LM-error	95.139	0.000***
	Robust LM-error	2.750	0.097*
LR 检验	LR-SDM/SAR	55.64	0.000***
	LR-SDM/SEM	66.22	0.000***
Wald 检验	Wald-SDM/SAR	56.82	0.000***
	Wald-SDM/SEM	67.23	0.000***
时空-时间固定效应检验	LR-both/ind	55.83	0.000***
	LR-both/time	534.37	0.000***

1）*和 *** 分别表示通过 10%和 1% 水平下显著性检验

3.6.3 空间杜宾回归结果分析

表 9 列（1）结果表明，在不考虑空间溢出效应的情况下，乡村数字技术对农业碳生产率的影响系数在 1%显著性水平下为 5.245，表明乡村数字技术的发展对农业碳生产率有显著提升作用；乡村数字技术的空间滞后项估计系数（26.045）在 1%显著性水平下为正，意味着数字技术发展通过空间溢出效应对邻近区域的农业碳生产率产生促进作用；空间自回归系数显著为正，表明农业碳生产率存在显著正向空间溢出。由于空间滞后项系数是本地和邻地

的加权值，并不能直接用来解释乡村数字技术对“促经降碳”的空间作用，故用偏微分分解为直接和间接效应。直接效应反映了乡村数字技术对本地区农业碳生产率的平均作用，即包括一个变量对农业碳生产率的直接影响以及该变量对相邻地区农业碳生产率产生的空间反馈效应。间接效应则反映了乡村数字技术的空间溢出作用。在地理距离矩阵、邻接矩阵和空间距离平方倒数矩阵下，乡村数字技术的直接效应和间接效应均为正，且都通过 1%的显著性水平检验。表明乡村数字技术在推动本区域农业碳生产率提升的同时，也在空间上呈现扩散溢出效应，可以对相邻地区的农业碳生产率起到促进效果，假设 2 得到验证。乡村数字技术对农业碳生产率影响的直接效应小于间接效应，表明乡村数字技术对邻近地区农业碳生产率的促进作用强于本地。这种现象可能的原因在于，乡村数字技术在本地应用后，其技术经验和创新成果通过区域间的技术扩散与知识溢出效应传播至邻近地区。相较于本地区独立探索和发展农业技术，邻近地区通过借鉴和应用现有成功模式的方法更为直接和高效，能够快速实现技术应用，使数据要素潜能充分发挥，实现了农业碳减排，达到提升农业碳生产率的目标。而本地由于已形成相对稳定的生产模式和技术应用水平，短期内进一步改进的空间有限，导致数字技术对本地农业碳生产率的提升幅度不及邻近地区。

表 9 空间计量回归结果 1)

Table 9 Results of spatial measurement regression

变量	地理距离矩阵(1)			邻接矩阵（2）		空间距离平方倒数矩阵（3）	
	空间杜宾模型	直接效应	间接效应	直接效应	间接效应	直接效应	间接效应
DIG	5.245***	6.014***	44.335***	5.764***	12.997***	5.812***	15.075***
	(1.125)	(1.169)	(16.997)	(1.097)	(2.619)	(1.110)	(4.613)
W×DIG	26.045***	—	—	—	—	—	—
	(6.109)	—	—	—	—	—	—
rho	0.321**	—	—	—	—	—	—
	(0.163)	—	—	—	—	—	—
控制变量	√	√	√	√	√	√	√
N	330	330	330	330	330	330	330
个体固定效应	√	√	√	√	√	√	√
年份固定效应	√	√	√	√	√	√	√
R^2	0.22	0.22	0.22	0.29	0.29	0.26	0.26

1）** 和 *** 分别表示通过 5% 和 1% 水平下显著性检验，“—”表示该项目不涉及的变量，“√”表示模型中已控制该项固定效应，括号内数值为稳健标准误

3.7 空间衰减特征

进一步研究乡村数字技术发展对农业碳生产率的空间溢出效应距离衰减特征。图 4 表明，空间溢出系数曲线呈现先增后减的趋势，乡村数字技术对农业碳生产率的空间溢出效应随距离阈值的增加表现出右拖尾倒“U”型特征。在 100~300 km 范围内，空间溢出效应显著为正且持续增强，并在 300km 处达到峰值（59.776）。这表明，在相对较近的地理范围内，区域间地理环境和气候特征的相似性使得农业生产结构和布局具有较高的趋同性，为数字技术的适应性应用提供了便利条件。然而，当距离阈值超过 300km 后，空间溢出效应开始衰减，至 700km 后系数趋近于 0 且不再显著。这种现象可能源于地理距离增加了技术交流的障碍，导致“降碳促经”效应出现空间衰减趋势。因此，尽管乡村数字技术通过区域间资源共享能够优化资源配置并降低碳排放强度，从而在邻近地区产生更强的农业碳生产率提升效应，但囿于技术扩散的地理局限性、区域间经济与社会联系的减弱、基础设施与政策支持的差异、知识溢出的局部性以及农业生产的地域性特征等多重因素的共同作用，其空间溢出效应仍表现出地理峰值和空间距离衰减现象，假说 3 得到验证。

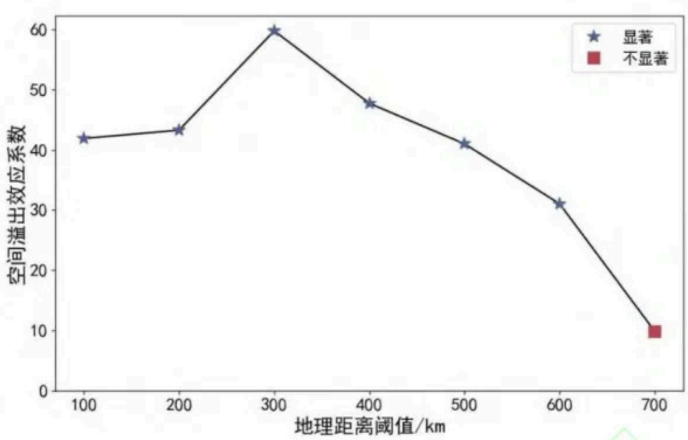


图 4 不同阈值距离下数字技术对农业碳生产率的空间溢出效应

Fig.4 Spatial spillover effects of digital technologies on agricultural carbon productivity at different threshold distances

4 建议

（1）完善乡村数字基础设施，深挖数字生态潜力。加大乡村数字基础设施的建设力度，推动“宽带下乡”和“数字乡村”战略，实现 5G 网络全覆盖；加大数字农业技术推广力度，加大农机购置补贴；设立乡村数字经济示范村，促进数据资源有序流通和价值释放，充分挖掘数据要素潜力，从而促进农业新质生产力成果转化为现实生产力，推动数字技术和数字经济深度融入农业领域，优化农业生产方式，助力农业低碳转型。

（2）探索差异化数字发展路径，分层次优化乡村生态收益。学习与总结中西部、粮食产销平衡区和粮食主产区的成功经验，因地制宜实时动态化的数字乡村发展模式，促进区域间的技术交流，对于“降碳促经”发展成效较好的地区，进一步巩固乡村数字技术带来的红利，对于发展成效一般的地区，要突破“卡脖子”技术，进一步研究适合当地的数字技术。

（3）优化数字空间布局，破除地区信息扩散壁垒。乡村数字技术对农业碳生产率存在正向空间溢出效应，但是存在倒“U”型地理衰减问题，应在 300km 范围处重点布局数字基础设施，使数字技术最大程度“嵌入”农业绿色生产中，实现最大化空间溢出效应；在 700km 范围处，建立跨区域的数字技术推广平台和人才交流机制，促进数字技术的扩散与应用，确保技术扩散的连续性，减少地理距离对技术溢出的阻碍。

5 结论

（1）2013～2023 年中国乡村数字技术水平呈现集聚特征，时间上发展水平呈现上升态势，空间上呈现由东向西梯度递减的空间分布格局，区域间发展不平衡问题仍然存在。农业碳生产率呈现逐年上升态势，在西南地区出现“高-高”集聚特征，区域间差异逐渐缩小。

（2）乡村数字技术发展对农业碳生产率的提升有显著作用，通过稳健性和内生性检验，结论依旧成立。异质性分析中揭示了在不同区位条件下，数字技术对农业碳生产率的提升效果在中部和西部远大于东部；在不同农业资源禀赋条件下，乡村数字技术在粮食产销平衡区和粮食主产区均能显著提升农业碳生产率。表明在制定与应用数字技术时，要考虑地区特定的基础设施和资源禀赋，制定差异化的绿色发展政策。

（3）乡村数字技术发展对农业碳生产率存在显著的正向空间溢出效应，但是存在倒“U”型地理衰减特征，当地理阈值达到 300km 时，空间溢出效应系数达到峰值；当地理阈值达到 700km 时空间溢出正向效应不再显著，表明乡村数字技术对农业碳生产率的空间溢出密集半径为 300km，空间溢出边界为 700km。

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03

文学

LITERATURE

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比较文学文献学：交流关系的三种形态与文献分布

张哲俊

内容摘要：比较文学文献学是以阅读书目校注交流关系的方法，以这种方法校注会发现交流关系的多种形态。近200年以来比较文学研究史中文学关系只有一种，即法国学派一对一的线状关系。但实际上法国学派的线性关系是源流关系，而非交流关系。交流关系也存在线性关系，其性质与法国学派的线性关系不同。其实除了线性关系之外还存在网状关系、常见关系，网状关系是多点多线的交流关系，是由典据范围的复数阅读书目用例构成的。这种交流形态与线性关系不同，不是锁定的交流关系，而是模糊的交流关系，迄今尚未发现先行研究描述过网状关系。常见关系是没有交流对象的交流关系，需要采用不同的研究方法。

关键词：比较文学文献学；典据；线性关系；网状关系；常见关系

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Title: Comparative Literature Philology: Three Forms of Exchange Relationships and Literature Distribution

Abstract: Comparative Literature Philology is a method of reading bibliographies and noting their relationships. Employing this method, one can discover various forms of exchanges. In the past 200 years, the only type of exchange in comparative literature has been the one-to-one linear relationship of the French school. However, the linear relationship of the French school is a genealogical relationship, not an exchange relationship. Exchange relationships also exist in a linear form, with a different nature from the linear relationship of the French school. In fact, besides linear relationships, network relationships and common relationships also exist. Network relationships are multi-point, multi-line exchange relationships formed by the multiple reading bibliographies used as examples within the scope of the data. Unlike the linear relationship, which is a fixed exchange relationship, the network exchange is a vague exchange relationship form. To date, no prior studies have fully described such network relationships. Common relationships, on the other hand, lack a specific exchange subject and therefore require alternative research methodologies.

Key words: Comparative Literature Philology; canon; linear relationship; network relationship; common relationship

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异国之间的交流关系研究是比较文学的重要领域，近 200 年以来先行研究描述的文学关系无非两种，一是影响关系，一是平行关系。平行关系实际没有文学关系，这样就只有一种文学关系，即法国学派描述的影响关系。影响关系是一对一的文学关系，只有一个影响对象，只能形成两点一线的线性关系，一般总结为 A + B 的文学关系，① 这是锁定封闭的文学关系。以比较文学文献学的方法注释与研究，阅读书目也会只有一个用例，也就只有一个典据，形成典据关系，其实也是 A + B 的线性关系。日本与韩国的校注本常用中国文献，说明语词的意义或来源，也就时常注释线性关系。显然以注释方式研究文学关系，是久已存在的古典文献学方法，线性关系亦早已存在，只是没有使用比较文学文献学的用语而已，比较文学文献学并无新的发现。但两种线性关系并不相同，法国学派的影响研究或古典文献学的注释方法没有引入阅读书目，是以一般书目研究文学关系。这种差异使新旧两种线性关系的性质完全不同，在旧的线性关系中没有典据，没有交流对象。没有使用阅读书目，就比较容易出现讹误。比较文学文献学以阅读书目注释，也描述线性关系，但能够修正错误，提高注释交流关系的准确性，这是建构比较文学文献学的目的之一。

一、线性关系：典据用例与锁定的交流关系

比较文学文献学是以诗人的阅读书目校注与研究交流关系的方法，迄今尚未发现近 200 年的比较文学研究史中出现过比较文学文献学，这是原始创新的文献学方法。② 以阅读书目校注会看到完全不同的交流关系风景，可以发现存在新旧两种线性关系。新旧线性关系究竟存在怎样的不同性质，还需要具体地研究。

“北人遮莫不知梅，九里千株手自栽。明主龙飞南国化，欢颜花亦放春开”（瑞溪周鳳 573）。日本五山诗僧瑞溪周凤的这首诗歌存在校勘与注释的问题，题目《画梅》旁题注：“图上木王元章《梅先生传》”。这里的“图上木”，疑“木”字为抄字之误，或为图上抄，图上抄录了中国元末明初诗人王冕的《梅先生传》的一段文字。题注记载的王冕《梅先生传》是直白明确的信息，表明瑞溪的《画梅》与《梅先生传》或王冕别集存在线性关系。顺着这一线索调查，确实能查到相关的信息，证明锁定这一线性关系是正确的：

其一，《梅先生传》载于王冕的《竹斋集续集》。王冕的《梅先生传》记载“先生名华，字魁，不知何许人，或谓出炎帝，其先有以滋味干商高宗，乃召与语，大悦曰：‘若作和羹，尔为盐梅。’因命食采于梅，赐以为氏。梅之有姓，自此始。〔……〕太史公曰：梅先生，翩翩浊世之高士也。观其清标雅韵，有古君子之风焉。彼华腴绮丽，乌能辱之哉！以故天下人士景爱慕仰，岂虚也耶！”（王冕，《竹斋诗续集》274—276）王冕《梅先生传》应当是瑞溪《画梅》的交流对象，存在一对一的线性关系。

其二，瑞溪《画梅》的“九里千株手自栽”是指王冕在九里山种植了千株梅树，这一信息亦见于《竹斋集 • 九里山中》卷上：“其一：荒苔丛篠路萦回，绕涧新栽百树梅。花落不随流水去，鹤飞常带白云来。”“其二：九里先生两鬓皤，今年贫胜去年多。敝衣无絮愁风劲，破屋牵萝奈雨何。”“其三：九里溪头晚雨晴，松风瑟瑟水泠

泠。绝无过客问奇字，只有闲云到野亭”（王冕，《竹斋诗续集》50—51）。《竹斋集·丁酉岁元日》卷中：“九里山中授时无，历日献岁喜天晴。道路何艰阻，山林似太平。梅香清海国，柳色上江城。且喜兰台近，疲民稍慰情”（王冕，《竹斋集·丁酉岁元日》133）。这些诗歌都记述了王冕在九里山种梅之事，是验证《竹斋集》与瑞溪《画梅》线性关系的重要证据。王冕写了九里山种梅之事，瑞溪的《画梅》也写了王冕九里山种梅，说明瑞溪应当从《竹斋集》获取了信息，表明二者之间存在线性关系。到此为止以一般书目注释与研究了线性关系，无论是法国学派或古典文献学都会采用相同的方法，也会得到相同的结论。

但这里存在一个小问题：瑞溪记载的“九里千株”与王冕的“新栽百树梅”不同，千株与百树的差异只是微不足道的问题，不足以改变《画梅》与《竹斋集》的线性关系，也就可以不去理会：在千株的注释中不提及百树，或者完全不出注，恐怕也没有人提出意见，可以锁定这一线性关系。如果研究与处理这一差异，通常会认定为变异。变异是文学关系的普遍现象，线性关系也存在变异。这一线性关系的性质是源流关系，《竹斋集》是典源，自然就是源，《画梅》是流。源流关系的基本特征是线性关系，变异是源流关系、线性关系的一部分：源流关系存在变异，也就有了发展；变异存在于线性关系，同一条线的前后文本不同，就表明产生了变异。变异不会改变线性关系的性质，反而使线性关系更为明显。源流关系不是只能有一条线，但变异只能存在于同一条线。

百树与千株的差异还存在另一种可能性，《画梅》与《竹斋集》的微小差异不是变异，而是另有文献来源。如果以阅读书目注释，会发现《竹斋集续集》未见于阅读书目清单，《梅先生传》亦未见于阅读书目的类书与总集、选集，这就有理由怀疑《梅先生传》或《竹斋集》并不是交流对象，《画梅》与《竹斋集》的线性关系及其变异并不正确。在阅读书目的范围内展开调查，可以证明这种怀疑是正确的。阅读书目确实可以提供《画梅》王冕种梅千株的信息，明宋濂的《文宪集》卷十的《王冕传》：“（王冕）乃携妻孥隐于九里山，种荳顷亩，粟倍之。种梅花千树，桃、杏居其半。芋一区，薤、韭各百本。引水为池，种鱼千余。头结茅庐三间，自题为梅花屋”（宋濂 552）。此传记载王冕在九里山种千株梅树，与“九里千株手自栽”的诗句完全相合。“明主龙飞南国化”指明太祖在洪武元年（1368）正月初四日，在应天府（南京）登基为君王，国号大明，年号洪武。南国化指南方化归大明，亦指王冕归附明太祖。《王冕传》：“未几，汝颍兵起，一一如冕言。皇帝取婺州，将攻越，物色得冕，寘幕府，授以谘议参军”（宋濂 552）。阅读书目的用例只有一个，也就只有一个交流对象，就是宋濂的《王冕传》，典据用例与典据书目、篇目同在一条线上。《文宪集·王冕传》为线性关系的一点，瑞溪周凤《卧云藁·画梅》为线性关系的另一点，形成了两点一线的线性关系。在这条线上只有千株，没有百树；没有差异，也没有变异。瑞溪诗歌的信息只能来自《文宪集·王冕传》，此外没有其他的可能性，所有信息是吻合的，这是锁定的典据关系。

两种文学关系都是线性关系，但是形态与性质都不相同。《画梅》与《竹斋集》的线性关系是源流关系，存在典源与变异，没有交流对象。《画梅》与《王冕传》的

线性关系是交流关系，存在交流对象，没有变异，只有典据。源流关系显示的是同一线性关系前后文本的传承与变化，前后文本之间不是交流关系，晚出文本的语词、事物用例不一定来自典源文本，除非早出的文本只有一种。交流关系显示的是诗人获取语词、信息的直接来源，交流关系的性质是存在交流对象，没有交流对象就不存在交流关系。阅读书目能够提供交流信息，自然就是交流对象。

那么两种线性关系哪一条是正确的？或者没有正误？源流关系与交流关系只是角度不同，并无正误，这是人文学科研究者最容易产生的看法。不过这种看法适用于文学性的研究，未必适用于交流关系的研究，交流关系研究是事实研究，与文学性研究不同。在没有引入阅读书目之前，一般都会认为千株是《画梅》与《竹斋集》线性关系的变异。瑞溪本来应当获取百树的信息，只是写诗时发生了变异，变异的原因已经无法查明，但可以展开各种分析与解释：瑞溪周凤粗心大意，或者记忆失误。如果是失误，那么可以根据《竹斋集》校勘。《竹斋集》是典源，以典源为据，可以将千株校勘为百树。如果是变异，或产生于瑞溪的夸张或想象，诗人原本就有夸张想象的特权，或者瑞溪周凤想要塑造更为痴爱梅树的王冕形象。但各种分析与阐释多是主观看法，不能证明变异是正确的，也不能解释产生变异的原因。一旦发现千株的信息来自宋濂的《王冕传》，变异就会消失，有关变异的分析与阐释，都会变得荒诞可笑。分析阐释的事实依据不存在，有关事实的分析阐释自然也会化为乌有。源流关系也是事实，并非全部都是事实，但很容易以为全部都是事实，这样变异也就成了事实。《竹斋集》是源流关系的源，这是事实，但变异不是事实。以阅读书目研究，可以发现另一种事实：瑞溪周凤是从宋濂的《王冕传》获取了《画梅》的所有信息，包括千株的用例，这是交流关系带来的结果。以源流关系研究，也可以查到宋濂的《王冕传》《竹斋集》亦载《王冕传》，题为《竹斋集传》，是后人作为附录载于《竹斋集》。

但是查到源流关系中的宋濂《王冕传》，也会陷入困境：两种结果都有可靠的文献依据，难免犹豫不决：题注记录的是王冕的《梅先生传》，瑞溪诗歌写的是王冕，这是最为有力的证据。但《王冕传》可以提供所有的信息，信息高度吻合。在没有引入阅读书目之前，《竹斋集》与《王冕传》都是一般书目，难以判断哪一种书目文献更有价值。按照古典文献学方法的注释，典源更加可靠，选择《竹斋集》的可能性大得多，这就等于承认存在变异。引入阅读书目之后，一切都会发生变化：《文宪集·王冕传》作为阅读书目，不仅提供了瑞溪诗歌的所有信息，还证明了瑞溪诗歌的信息来源。这是典据，典据才是真正的信息来源，是交流关系的标志，前阅读书目阶段无法提供这样的信息。对源流关系来说，典源更为重要；对交流关系来说，典据更为重要。但现在的问题不是哪一个更为重要，而是究竟有无正误的问题。从源流关系来看，《画梅》的千株是从王冕诗歌的百树变化而来，但事实是来自《王冕传》的千株。这就意味着源流关系的描述并不正确，不同的角度的确可以产生不同的看法，但并不表明没有正误，源流关系描述的准确率不如交流关系。《王冕传》证明了阅读书目的有效性与可靠性，以阅读书目注释能够修正以一般书目注释的结果，交流关系的研究结果，也可以修正源流关系的部分看法。

那么源流变异的错误看法是如何产生的？没有引入阅读书目，源流关系与交流关系严重纠缠，必然混同源流关系与交流关系，不知道存在两种线性关系，更不知道变异存在于哪一条线性关系。只有能够了解千株存在于哪一条线，才能知道同一线性关系的前后文本关系，才能知道千株是变异还是典据。千株与百树不存在于同一线性关系，千株不存在于源流关系，而是存在于交流关系。瑞溪从已经发生变异的《王冕传》中获取了千株，这样瑞溪诗歌的千株也成为了变异。但变异发生于中国，不是发生于日本，瑞溪的《画梅》中没有变异。研究者很容易将中国文学的变异当成日本文学的变异，这样必然会出现错误的结论。以阅读书目注释交流关系，就不会出现变异的错误看法。源流关系的变异可能是真正的变异，也可能是虚假的变异。真假变异的问题其实是文献问题，找到最重要而又准确的文献是解决问题的唯一方法。以阅读书目注释与研究是找到这种文献的捷径，阅读书目能够区别源流关系与交流关系的差异，也能够清清楚楚地了解到真假变异，能够修正错误，这是建构比较文学文献学的意义所在。比较文学文献学的主要价值之一是能够提高注释交流关系的准确性，如果以阅读书目注释，无法提高准确率，比较文学文献学也就丧失了存在的意义。如果没有阅读书目，就只好退到源流关系，但无法了解变异是否正确，也不知道是否存在交流关系，但应当明白源流关系不能当成交流关系。源流关系存在变异，交流关系也存在变异，只有能够区别两种线性关系，才能知道是源流关系的变异，还是交流关系的变异。

以阅读书目注释线性关系的另一问题，是锁定典据书目的问题。典据用例、典据篇目与典据书目必须存在于同一条线上，才能形成线性关系。但是同一篇目可以收入于不同的阅读书目，尤其是名篇佳作更是容易收入于多种阅读书目，这就存在能否锁定典据书目的问题。能够锁定典据书目，就存在完整的线性关系；不能锁定典据书目，就存在非完整的线性关系，即线性关系与典据书目范围的结合形态。解决这个问题不能停留在阅读书目层面，必须进入到更为细小的层面，信息量与吻合度有可能是锁定典据书目的依据。

《鸟语山容开》一诗云：“晴咔声中紫翠开，笑容娇语喜谁回。问山未答鸟先答，去岁春风今岁来”（瑞溪周鳳 532）。根据瑞溪周凤《鸟语山容开》的诗题来看，典据篇目与用例是苏轼的《东坡诗集注·闻辩才法师复归上天竺以诗戏问》卷二一：“忽闻道人归，鸟语山容开。神光出宝髻，法雨洗浮埃”（王十鹏，《东坡诗集注·闻辩才法师复归上天竺以诗戏问》421）。此诗又载于《东坡全集》卷九、《施注苏诗》卷十四。典据用例、篇目是明确的，但难以明确典据书目。如果《东坡诗集注》《东坡全集》《施注苏诗》都是信息来源，那么会形成典据关系与典据书目范围的组合，即线性关系与网状关系的组合形态。三本苏轼别集都是阅读书目，又都有《闻辩才法师复归上天竺以诗戏问》诗，提供等量信息，也就无法锁定典据书目。不过《东坡诗集注》的注文提供了重要的信息，注文引用了苏辙的文章：“子仁按：子由《辩才塔碑》云：‘沈公遘治杭，以师住天竺灵感观音院。有僧文捷者，利其富，倚权贵人夺而有之，迁师于下天竺，又逐师于潜。逾年而捷败，复以上天竺与师。捷之在天竺也，岩石草木为之索然。及师之复山中，百物皆若有喜色。’赵公抃亲见而赞之，曰：‘师去天竺，山

空鬼哭。天竺师归，道场光辉，即先生今诗意也’”（王十鹏，《东坡诗集注・闻辩才法师复归上天竺以诗戏问》421）。“鸟语山容开”描写了辩才法师回归天竺寺的自然景象，瑞溪的诗歌也写了相关的内容。《东坡全集》没有注文，《施注苏诗》的注文与《东坡诗集注》不同，没有记述辩才法师回归天竺灵感观音院之事，因而可以确定《东坡诗集注》是典据书目，典据用例、篇目与书目形成了线性关系，这是靠信息量与吻合度来锁定线性关系的。

不过问题并没有完全解决，《辩才塔碑》是苏辙的《龙井辩才法师塔碑》，见于《栾城后集》卷二四。《栾城集》也是阅读书目，这就意味着还存在另外一种可能性：瑞溪读了《东坡全集》与《施注苏诗》之后，又读了苏辙的《龙井辩才法师塔碑》，然后将源于不同书目的内容信息合并在一起。这种可能性是存在的，这就意味着前面已经锁定的线性关系未必可靠，只有解决了瑞溪诗歌与《栾城集》的交流关系问题，才能最后证明瑞溪诗歌与《东坡诗集注》的线性关系。那么如何解决这一问题呢？信息量与吻合度仍然是解决问题的途径：瑞溪《鸟语山容开》的内容范围，没有超出《东坡诗集注》注文的引用部分，这说明《东坡诗集注》是典据书目。苏辙的《龙井辩才法师塔碑》是一篇较长的文章，比较完整地记述了辩才法师的一生，内容相当丰富，远远超出了《东坡诗集》注释引文的内容范围。超出的信息没有进入到《鸟语山容开》诗的文本，没有成为信息的来源，说明瑞溪根据苏轼诗歌与苏辙《龙井辩才法师塔碑》作诗的可能性是不存在的。瑞溪诗句“去岁春风今岁来”是写辩才法师去年离开、今年复归之事，这一内容亦见于注文引用的“逾年而捷败”。“问山未答鸟先答”一句的内容不见于《龙井辩才法师塔碑》，但见于苏轼的诗句“鸟语山容开”，即瑞溪诗歌的内容全部来自苏轼的诗歌及其注文的苏辙《龙井辩才法师塔碑》引文。《东坡诗集注》与注文提供了比《东坡全集》与《施注苏诗》更为丰富的信息，可以满足瑞溪诗歌需要的信息量。苏辙《栾城集・龙井辩才法师塔碑》也是阅读书目，信息量更为丰富，但没有为瑞溪周凤的《鸟语山容开》的文本所用，并不是瑞溪诗歌需要的信息。《东坡诗集注》与注文信息量同瑞溪诗歌的信息量高度吻合，可以锁定《东坡诗集注》是典据书目，也就形成了完整的线性关系。

信息的吻合度是由两个方面构成的：一是两种文本的语词用例、信息内容的吻合度，如果语词的字词与信息内容存在差异，就表明不存在交流关系，或者存在变异。二是信息量的吻合度不是指信息量越多越好，也不是信息量越少越好，最好是阅读书目提供的信息量与诗歌文本需要的信息量大体吻合。信息量丰富的文本比信息量较少的文本，更容易成为线性关系的典据书目。信息量不足，说明可能不存在线性关系，或者另有线性关系的阅读书目。信息量的多少是以接受信息的文本为依据，瑞溪《鸟语山容开》中的信息量是判断的基准。《东坡诗集注》提供了基本相合的信息量，《栾城集》提供了过多的信息量，但又缺少苏轼诗歌文本的信息。《东坡全集》《施注苏诗》没有能够提供瑞溪《鸟语山容开》的部分信息，信息量较少，说明不存在线性关系。

二、网状关系：典据范围与模糊的交流关系

线性交流关系不是全部交流形态，此外还有网状关系，这是比线性关系更为多见的交流形态，也应当成为研究的重点。

第一，网状关系的模糊性质与线性关系的差异。

网状关系不同于线性关系，阅读书目不是只有一个用例，而是出现了复数的用例，交流形态发生了变化，性质也有了不同。下面根据瑞溪周凤的诗歌《前圆觉茂伦禅师，见居羽之崇福常在禅庵……》来看看网状关系的形态与性质：“双桂座中会见之，重来未面早相知。莺花能记旧游否，前度刘郎鬓已然”（瑞溪周鳳 548）。“前度刘郎”是指刘禹锡再次入京，在此喻指茂伦禅师再来京都。“然”当校为丝。前度刘郎一语出于阅读书目《刘宾客文集·再游玄都观绝句并引》：“余贞元二十一年为屯田员外郎，时此观未有花木。是岁，出牧连州，寻贬朗州司马。居十年，召至京师，人人皆言有道士手植仙桃，满观如红霞，遂有前篇以志一时之事。旋又出牧，于今十有四年，复为主客郎中。重游玄都，荡然无复一树，唯兔葵燕麦动摇于春风耳。因再题二十八字，以俟后游。时大和二年三月。百亩中庭半是苔，桃花净尽菜花开。种桃道士归何处？前度刘郎今独来！”（刘禹锡 308）前度刘郎写的是刘禹锡之事，出于《刘宾客文集》，《再游玄都观绝句并引》是典源，其中存在典源本事与语词用例。如果阅读书目只有《刘宾客文集》的用例，那么典源用例与典源本事同时也是用例典据与本事典据，会形成线性关系。但其他阅读书目也有用例，这样《刘宾客文集》就不是典据用例与典据本事。《旧唐书·刘禹锡》卷一六〇、《锦绣万花谷前集》卷三、《古今事文类聚后集》卷三一、《全芳备祖前集》卷八、《平广记·刘禹锡》卷四九八、《诗话总龟》卷二九、《诗林广记》卷四等，都是既有用例，也有本事。有的选集只选诗歌，不载本事，《万首唐人绝句》卷五就是只有刘禹锡诗歌，没有本事。有的诗文只用“前度刘郎”的语词用例，不记本事，《东坡诗集注·留别释迦院牡丹呈赵倅》卷十：“去年崔护若重来，前度刘郎在千里”（王十鹏，《东坡诗集注·留别释迦院牡丹呈赵倅》169—170）。《东坡全集》卷八、《施注苏诗》卷十一、《秋崖集》卷二三、《北磵集》卷八、《江湖小集》卷六七等阅读书目，也都只有语词用例。在本事的流行过程中，“前度刘郎”成为了本事的标志性语词，即使没有记录本事，本事已经内含于标志性语词，这是因为语词用例与本事内容已经合而为一。上述阅读书目的复数用例构成了典据范围，典据范围的所有用例交集于瑞溪诗歌的前度刘郎一词，形成了网状关系。

网状关系是交流形态与性质的描述：首先，网状关系的交流形态。网状关系的交流不是产生于两点一线，而是产生于多点多线。多点是指阅读书目有复数用例，多线是指阅读书目的复数用例与注释语词之间存在复数的交流线。线性关系只有一个阅读书目的用例，也就只有一条线，语词用例与信息只能通过这一条线性关系来交流，这是一条交流实线。网状关系多点多线的最低数量是阅读书目有两个用例，多则十余例或二、三十例。存在两个以上的交流对象，也就存在两条线以上的交流线，多则十几条线或二、三十条线。其实只有两条交流线，难以形成网状关系，但两条线的交流关

系与网状关系的性质没有不同，这是网状关系的起点。阅读书目的用例数量决定了交流形态，从零到一是有无交流关系的标志，没有阅读书目用例，就表明不存在交流关系。存在一个阅读书目用例，就只能是典据或典据关系，即线性关系。存在复数的阅读书目用例，就表明存在典据范围、网状关系。典据关系与典据范围的界线是清晰明确的，二者的关系彼此对立：只要是典据关系，就不可能是典据范围；是线性关系，就可能是网状关系，反之亦然。前度刘郎的阅读书目共有 15 例，也就存在 15 条线，都连接于瑞溪诗歌，汇织为了一张网。这是典据范围，也是网状范围。

其次，网状关系的模糊性、整体性与线性关系的不同性质。线性关系是锁定的交流关系，网状关系是模糊的交流关系。模糊的原因是无法锁定特定的交流对象，也无法锁定特定的交流关系。但并不表明无法确定是否产生过交流关系，可以确定交流关系产生于典据范围或网状范围之内。典据范围或网状关系作为一个整体可以证明发生过交流关系，但典据范围的每一用例都只是可能性，不能确证发生过交流关系。因而典据范围的用例不能拆解，只能是整体的一部分。如果能够拆解为各自独立的每一条线，那么网状关系必然是线性关系的叠加，网状关系就不复存在。典据范围的每一用例都是疑似典据，永远也无法锁定为典据，因而典据范围的用例与典据用例性质完全不同。典据与典据范围是对立关系，是典据，就不可能是典据范围，反之亦然。信息量和吻合度也是研究网状关系的基本依据，但典据范围的用例提供了等量信息与吻合度，无法通过信息量与吻合度来锁定线性关系。阅读书目前度刘郎的用例有两类，一是有本事记载，一是没有本事记载，信息量并不均等，应当能够锁定典据或线性关系。但信息量与吻合度从来都不是单向测定，而是双向测定：注释语词的信息量与阅读书目用例信息量的吻合度。瑞溪诗歌只有“前度刘郎”四个字，这样没有记载本事的阅读书目用例，就不能归入于典据范围。但本事内容包含于“前度刘郎”的四个字，无论是否记述本事内容，都是提供了等量信息，都是典据范围，是网状关系的一部分。这张网中的线有长有短，有远有近，有诗人常用的阅读书目，也有不常用的阅读书目，但这种距离差异不足以锁定典据。距离最近的是《东坡诗集注》，这是瑞溪常用的书目，但仍然只是网状关系的一条线。《秋崖集》《江湖小集》不是瑞溪最常用的阅读书目，距离最远，但也不能逐出典据范围，网状关系的交流形态没有改变。

产生网状关系的原因比较多，一部分原因来自诗人的记忆方式，一部分来自外在因素：首先，确定而又不确定的交流关系与潜移默化的契合。网状关系确定而又模糊，如果每一条线明确而又清晰，那么有多少阅读书目的用例，就有多少条线性关系。线性关系与网状关系来自不同的记忆方式，潜移默化的记忆方式与网状关系的交流形态完全吻合。诗人的记忆可以在一次阅读中完成，也可以多次阅读中完成。或者是一次阅读中完成记忆之后，又会不断遭遇，进而不断强化记忆；或者是在阅读不同阅读书目的过程中逐渐留下深刻的记忆。其实只要研究交流关系，总会触摸到典据范围的网状关系，但至今没有看到发现网状关系的报告。引入阅读书目之前，潜移默化过于模糊神秘，难以作为研究对象。引入阅读书目之后，潜移默化的过程仍然不可描述，但潜移默化的结果即典据范围是可描述的，也就可以作为研究对象。典据范围的可描述性

建立在阅读书目清单的基础上，限定了交流关系的范围。阅读书目的复数用例限定了典据范围的边界，这样就可以触摸到典据范围的边界，也就可以记述典据范围的边界。以一般书目注释交流关系，没有交流关系的可能性范围，就无法触摸典据范围的边界，自然就无法描述典据范围。反复阅读与潜移默化是阅读的基本特征，潜移默化不是无边无际，无迹可寻，而是存在于一定的范围之内，这个范围就是典据范围，也是网状关系的范围。

其次，书籍的编辑方法。一篇诗文可以收入于诗人别集，也可以载于总集、选集以及类书。前度刘郎出于刘禹锡的诗歌，载于刘禹锡的《刘宾客文集》。刘禹锡的《再游玄都观绝句并引》是名篇，也就非常容易载于总集、选集等，《万首唐人绝句》是唐人绝句的选集，自然会收入刘禹锡的这首诗歌。《锦绣万花谷前集》《古今事文类聚后集》《全芳备祖前集》《平广记》是不同类型的类书，收入《再游玄都观绝句》也是理所当然，以便于文人经常查找使用。《诗话总龟》《诗林广记》是诗话，诗话的主要功能之一是记录与品评名篇佳作，因而刘禹锡的诗歌出现于诗话。《旧唐书》是官修正史，刘禹锡本传的主要内容是刘禹锡的仕途经历与诗文创作，载入《再游玄都观绝句》是官修正史编撰的正常范围。《再游玄都观绝句》出现于以上多种阅读书目，瑞溪周凤必然时常碰到刘禹锡的诗歌。除了书目的编辑之外，不同版本、不同校注本也是出现网状关系的原因。《东坡全集》《东坡诗集注》《施注苏诗》等等，都是苏轼的别集，也都是阅读书目，这样就容易反复阅读。

再次，诗文使用语词与典故的方法。诗人常用典故来表现生活与情感，阅读就必然会不期遭遇诗文的典故用例，这也是诗人记忆来源的一部分，也是形成网状关系的原因之一。前度刘郎出现在《东坡诗集注》《秋崖集》和《江湖小集》，是作为典故使用的。瑞溪周凤熟读《东坡诗集注》，必然会触及《东坡诗集注》中出现的前度刘郎。《秋崖集》是宋代诗人方岳的别集，《北磵集》是释居简的别集，《江湖小集》是宋人诗歌选集，也出现了前度刘郎的用例。瑞溪周凤在阅读过程中也就可能遭遇这些不同阅读书目的用例，也就能够成为典据范围的一部分。这都是来自古代诗人不断使用同一典故的创作方法，诗人喜欢用事，读者也得了解用事的内容，这种交流关系是形成典据范围的原因之一。典据范围或网状关系并不难以理解，只是以一般书目无法描述，先行研究也就未能作为研究对象。

第二，网状关系的多种形态与可描述性。

首先，网状关系的基本形态。网状关系的基本形态有二：一是阅读书目的复数用例都与注释对象的语词存在交汇关系，即以注释文本的语词为中心，所有阅读书目的用例与中心存在虚实模糊的交汇关系，这是网状关系的基本形态。前文瑞溪诗歌的“前度刘郎”与 15 个阅读书目用例的关系，就是属于这种形态，复杂的网状关系是这一基本形态的变化。二是网状关系存在于书目层面与篇目层面、用例层面，三个层面的网状关系可以各自独立，但交集于用例层面，或交集于用例与篇目的层面，这样就会形成彼此交错的网状关系。前度刘郎是用例层面，注释文本的语词用例与阅读书目的用例构成用例层面的交流关系。阅读书目的用例层面存在两种类型，一是语词用例，一

是本事用例，两种用例可以合而为一，也可以各自独立。篇目层面只有一个篇目，那么就不会形成网状关系，只有典据篇目。但同一用例载于不同篇目也很普遍，也就会形成篇目的网状关系。书目层面只有一个书目，就会形成典据书目，也就不会形成书目层面的网状关系。但同一名篇佳作经常收入于不同书目，同一用例载于不同篇目，不同篇目又载于不同书目，也都是形成书目层面网状关系的原因。前度刘郎出现于刘禹锡的《再游玄都观绝句》，此诗又载于不同阅读书目，用例、篇目就成了交集之处，这样会形成书目层面的网状关系。前度刘郎出现于苏轼的篇目，苏轼的篇目又载于不同的苏轼别集，必然形成又一网状关系。前度刘郎还出现于《秋崖集》《北磵集》《江湖小集》，书目不同，篇目也不同，这就会形成又一网状关系。网状关系存在很多交汇点，但中心交汇点只有一个，就是注释的语词与本事。瑞溪诗歌的前度刘郎是中心交汇点，与 15 条用例存在着交流的虚实关系。③

其次，网状关系的复杂形态。一条语词有一个网状关系是基本形态，但一条语词可以存在多个网状关系，或网状关系与线性关系的组合形态。线性关系与网状关系是对立关系，那么两种关系如何共在，又是形成了怎样的交流形态？是否显示了交流关系的事实？

瑞溪周凤《次前韵寄卿云侍者并叙》：“卿云有族兄，与之亲甚，不暂相见，则食不甘味。姜氏之被乎？苏公之床乎？五王之帐乎？”（505）姜氏之被是瑞溪周凤化用了姜肱被或姜被，指兄弟之情，五山文学或中国文学没有用例，但有姜肱被或姜被的用例，此外还有本事用例，这样就可以出现三条交流关系：一是阅读书目的本事用例，典源为《后汉书 • 姜肱传》卷八三：“肱与二弟仲海、季江，俱以孝行着闻。其友爱天至，常共卧起”（范晔 1749）。《资治通鉴》卷五四、《通志》卷一一〇、《太平御览》卷四一六、四二〇等均为本事典据范围。姜被亦有典据用例范围，唐杜甫《集千家注杜工部诗集 • 寄张十二山人彪三十韵》卷六：“历下辞姜被，关西得孟邻”（杜甫 770）。《九家集注杜诗》卷二十、三四，《集千家注杜工部诗集》卷六、十八，宋王十朋《梅溪前集》卷五、后集卷四等均为典据范围。二是姜肱被的阅读书目用例，仅见一例，只能形成线性关系，典据为宋方岳《秋崖集 • 次韵三四弟》卷十一：“二难宁共姜肱被，一染谁怜墨子丝”（方岳 432）。三是姜被用例的网状关系，宋郭知达编《九集集注杜诗 • 寄张十二山人彪三十韵》卷九、卷三四《秋日荆南送石首薛明府辞满告别奉寄薛尚书颂德叙怀斐然之作三十韵》和《集千家注杜工部诗集》卷六、卷十八以及宋计敏夫《唐诗纪事》卷二三均有用例，构成了又一个网状关系④。在三条交流关系中出现了两个网状关系与一个线性关系的组合形态，这表明一条语词的交流关系可以共存多个网状关系，网状关系也可以与线性关系共存。多个网状关系与线性关系又都交汇于注释对象的语词，大小不一的网状关系与线性关系以注释对象的语词为中心构成了大的网状关系，也就是大的网状关系内存在小的网状关系，或者小的网状关系与线性关系共在。

网状关系与线性关系共在是事实，对立也是事实，但这也不是不同角度的不同看法。网状关系是比较复杂的交流关系，多层面、多形态、多线条的交流是网状关系的

特征，一条语词的交流关系存在不同层面，又可分化出多条交流关系。本事用例、语词用例可以分化出两条交流关系。交流关系是以语词为单位，语词的字词不同，就会存在不同的语词用例，必然分化出不同的交流关系。语词的化用是出现分化线索的原因之一，瑞溪诗歌的姜氏之被就是化用，分化出了三条交流关系。分化的交流关系有各自的阅读书目，用例数量多少不一，也就可以存在多个网状关系，或是网状关系与线性关系共在。网状关系与线性关系不是同在于一条分化的交流关系，而是各自存在于不同的分化交流关系，这样没有改变网状关系与线性关系的对立性质。在同一分化的交流关系中，不可能同时存在网状关系与线性关系。每一条交流关系是独立的交流关系，但都交汇于瑞溪诗歌的姜氏之被，这样必然形成交叉的网状关系。不同路径存在不同的风景，如果合并分化出的多条交流关系，必然混同不同的风景。这样就只有一团乱麻，彼此纠缠矛盾，令人困惑不已，无法了解交流关系的具体形态。先行研究没有进入到分化层面，停留在同一语词、同一层面的交流关系，这样永远失去了了解交流关系的机会。

其次，潜在书目与阅读书目的网状关系形态。网状关系是群体交流的方式，交游圈与交游圈别集（潜在书目）也是群体交流的状态。复数的潜在书目（交游圈别集）可以形成典据范围，这是接受者的网状关系。五山文学也有前度刘郎的用例，几乎全部出于潜在书目，瑞溪周凤的《禁钟》也有用例：“刘郎今夜耳应熟，京馆归来花外闻”（533）。《次韵棠童试笔》：“犹期前度刘郎否，长乐晓钟花外声”（533）。瑞溪周凤的诗文弟子横川景三《再依等持某试笔》：“刚遭春恼再题句，桃动刘郎前度枝”（横川景三，『補庵集』31）。镰仓建长寺光岩老人的《红梅》：“若教曾在玄都观，前度刘郎不咏桃”（光巖老人 641）。光岩老人不是瑞溪交游圈的诗人，但其他用例出于瑞溪周凤与横川景三，也可以构成网状关系。五山文学前度刘郎的用例不多，更多见的用例是刘郎，瑞溪周凤《次韵仙童试毫寄令师明远和尚》：“刘郎去后春多事，道士桃花千树红”（552），《画轴》“刘郎白发拙于汝，孤负玄都千树春”（573）。惟肖得岩《松》：“玄都桃净尽，满地兔葵春。莫障西风扇，刘郎白髮新”（916）。横川景三《赋桃花送客》：“同参他夜（日）惟红雨，犹是刘郎去后春”（『補庵京華集後集』316）。西胤俊承《赠见花君子二首》：“刘郎双髩未遑染，落尽玄都千树花”（2738）。愕隐惠奯《次韵椾侍者题吸江二绝》：“刘郎若不恨春色，何管玄都观里桃”（2640）。西胤俊承与愕隐惠奯皆为绝海中津的诗文弟子，与惟肖得岩交游，稍早于瑞溪周凤。瑞溪与惟肖得岩交往甚密，但与西胤俊承、愕隐惠奯的交往没有那么深密。刘郎与前度刘郎不同，刘郎的用例也几乎都是出于交游圈别集，又形成一个网状关系，这样潜在书目出现了两个网状关系。

阅读书目存在网状关系，潜在书目也存在网状关系，二者之间存在何种关系？是一张网状关系的两个部分，还是两张网状关系？这是两张网状关系，阅读书目与潜在书目是两种不同的书目，也就不可能形成一张网状关系。但两张网之间存在着交流关系，阅读书目的网状关系是潜在书目的网状关系的来源范围。瑞溪周凤的阅读书目也可以是交游圈诗人共同的阅读书目，《刘宾客文集》与《东坡诗集注》等等阅读书目

也是瑞溪交游圈诗人的阅读书目。阅读书目的网状关系是原生交流关系，潜在书目的典据范围是次生交流关系。这样就存在三种交流关系：一是特定诗人别集与阅读书目的网状关系，二是特定诗人别集与潜在书目的网状关系，三是阅读书目与潜在书目的网状关系。这里只研究了前两种网状关系，没有研究第三种网状关系。第三种网状关系与前两种没有多少不同，也就没有必要描述。阅读书目与潜在书目各自独立，线性关系与网状关系亦可同在。阅读书目只有一个用例，形成了线性关系，但是潜在书目可以存在复数用例，必然形成网状关系。有的语词在中国文学中并不流行，但在日本文学中十分流行，其具体体现方式之一就是线性关系与网状关系同在。

网状关系与线性关系不同，注释方法也会不同，描述网状关系需要记述阅读书目及其用例，注释方式有二：一是可以列出所有典据范围的书目与用例，⑤二是只列少量典据范围的书目与用例，其余只记书目清单。理论上说注释应当注出典据范围的所有用例、篇目与书目，这样才能提供典据范围的完整信息。然而记述典据范围的所有用例，必然大大增加篇幅。为了节省篇幅，一部分用例可以只记述书名、篇名、卷号，省略用例引文。这样可以大大地节省篇幅，但还是能够提供最低限度的交流信息，仍然可以描述典据范围。描述网状关系不可以随意选取一例或几例，随意删减必然破坏交流信息的完整度，这是由典据范围的整体性质决定的。网状关系的注释与古典文献学的注释似无不同，古典文献学的注释也会举证复数的文献用例，但与典据范围完全不同：首先，古典文献学注释的复数用例不一定来自阅读书目，并不一定包含文学关系的信息。典据范围的用例都是出自阅读书目，包含着交流关系的信息。其次，古典文献学注释的复数用例只是举例，并不表明任何边界，比较文学文献学注释的复数用例是标示交流范围的边界。后者的注释用例都是来自阅读书目，阅读书目是存在边界的范围，阅读书目的用例也就存在边界范围。大的边界范围是小的边界范围的前提，如果没有阅读书目的清单，也就不会有阅读书目用例的清单。古典文献学使用一般书目注释，也就无法触摸到交流范围的边界，能否显示交流范围的边界是古典文献学与比较文学文献学的重要差异，描述典据范围的边界是记述网状关系的基本方式。

三、无边关系：常见用例与开放的交流关系

常见关系是最为普遍的交流关系，与典据关系、典据范围的交流形态不同，是开放的交流关系，没有交流对象，也没有交流对象的范围，这是没有边界的交流关系。交流形态完全不同，也就需要采用不同的方法。

第一，基于常见字词的常见关系。

常见关系最多见于来自他国的常见语词，区域通用语言的基本词汇最易形成开放的常见关系。古代汉文是古代东亚的通用语言，很多中国的基本语词成为了东亚的基本语词，也成为了他国母语的一部分。其结果基本语词不需要从中国文献获得，在本国文献、日常生活中随处可见，也就可以随处习得。基本语词多是常见语词，最初源于中国，但随着广泛普遍的使用，丧失了与中国文学的交流关系，阅读书目、潜在书目、替代书目也会丧失有效性，也就无法从常见语词中确定典据关系、典据范围。这样以阅

读书目注释交流关系的方法也变得没有意义，也就不能采用以阅读书目注释交流关系的方法。

春、秋、风、雨之类常见词汇的意义不需要解释，也不需要注释。万里集九《蟄燕》“东山四处带春迟”（『梅花無盡藏・蟄燕　正法寺之会』三下 818）的春字，最初来自中国，应当存在文学的交流关系。然而春字早已成为日本母语词汇，无法根据春字找到交流关系，实际上也不存在交流关系。春字在中日文学中存在无数用例，五山诗人常用的阅读书目《艺文类聚》有 1424 个用例，《古今事文类聚》有 1975 个用例。其他的阅读书目以及日本文学、五山文学还有无数用例，这样也就不存在交流对象或交流对象的范围，只有无边开放的交流关系。丧失了交流对象的边界，也就无法描述。理论上无论用例有多少，还是可以记述两本类书的所有用例，但除了占用太多篇幅之外别无意义。常见语词的意义没有出注的必要，开放的交流关系也没有出注的必要，不过常见语词与常见关系的基准会有变化，这样还是存在是否需要出注的问题：

其一，常见语词、常见关系因时而异。基本语词有相当的稳定性，常见关系也有相应的稳定性。但不是所有的基本语词都是恒定不变，或者意义发生变化，或者交流关系发生变化。时间是基本意义或交流关系发生变化的判断基准：或者古今皆很常见，或者古今不同；或者古代特定时期常见，在另一时期并不常见。基本意义比交流关系稳定，基本意义没有变化，不等于交流关系没有变化。昼寝与午睡的意义相同，如果只注字面意义，都不需出注。昼寝与午睡都是来自中国文学，但在日本文学中流行的时间不同。昼寝是上古、中古一直使用的词汇，午睡是中世五山文学开始普遍使用的词汇⑥，常见关系形成的时间不同。午睡的基本意义没有变化，但是体现了五山诗人的特殊生活和特殊意义，即使交流对象的范围超出了一般状态，也是需要出注。

其二，常见字词的组合关系也是出注的基准。常见字词的组合关系可以产生典据关系或典据范围，这样也就需要出注。万里集九《有花即入门　序见别卷，放翁句云：‘有花即入门，莫问主人谁。’己亥春，共诸彦看尾之继鹿尾之花》：“三人卸笠坐花前，继鹿尾门并瑞泉。遗恨山房借无砚，数株香雪不留篇”（『梅花無盡藏』一 668）。诗题的有花、即、入门都是常见字词，每一字词只有常见关系，但组合为完整诗句，就可能存在交流关系。万里集九的诗题自注，标明诗题来自陆游的诗句“有花即入门”，这样就可以锁定典据用例，也就确定了典据关系。万里集九只注明陆游的诗句，没有注明陆游的诗句来自哪一本书。阅读书目有两本，《剑南诗稾・游东郭赵氏园》卷七和宋罗椅《放翁诗选后集》卷四，两本书目均收入《游东郭赵氏园》诗，二书均为典据书目的范围。常见字词的组合关系完全可以改变常见字词的常见关系，是否常见取决于组合关系。常见字词与组合关系是不同的注释对象，交流单位发生了变化，自然就有不同的交流形态，这是出注的基本依据。

第二，基于常识的常见关系与注释、研究的方法。

常见语词也可以是常见知识，但常见知识与常见语词有所不同，包含更为丰富的内容与信息，这就增加了出注的必要性。常见语词是构成区域语言基本词汇的基础，常见知识是构成区域知识共同体的主要部分之一。东亚文化圈的知识共同体是以中国的

知识、概念为主，其范围非常广泛，覆盖天文、地理、宗教、思想、医学、植物等等所有领域，这也是文化圈形成的基础之一。东亚文化圈的知识共同体是东亚共有的知识、概念，在此基础上可以形成开放的交流关系，但不一定像常见语词那样普遍。五言、七言等等都是中国文学的常识，也是五山诗人或日本文学的常识。五山诗人自少年时期入于禅寺学习汉文学，就开始接触各种文学知识，五言、七言很快就会成为常识。这样的常识与特定五言诗歌的文本是开放的关系，也就难以通过五言常识确定特定五言诗歌文本的交流关系。

基于常识、概念的常见关系也可出注研究，常见关系的特征是没有交流对象，也没有交流对象的范围，缺乏限定性，只有宽松自由的交流关系。此类交流关系也可出注与研究，只要选定的文本中存在交流因素，就可以自由地作为注释与研究的对象，这种研究方法与线性关系、网状关系的方法不同。试笔诗是古代诗歌的一种类型，是古代文人的常识，但不是现在的常识，因而需要出注研究。

如瑞溪周凤《次韵逸童试毫》：“春兴忽呼诸葛毫，吟兼莺啭一齐高。鲤庭花亦学诗否，桃自讽梅梅答桃”（539）。“试毫”即试笔。如果出注，就可以如此注释：试笔诗是中国古代诗歌的一种类型，五山文学时期传入日本，并成为了五山诗歌的类型，数量相当丰富。这样的注释简略注明了试笔诗及其交流关系，解决了阅读的一般需要，也就可以结束注释。但这样注释之后还存在其他问题：瑞溪的试笔诗与中国特定诗人的试笔诗是否存在典据关系或典据范围？欧阳修、苏轼、黄庭坚、陆游等人皆有试笔诗文，他们的别集均为阅读书目，但没有证据表明瑞溪的试笔二字来自欧阳修等人的试笔诗。瑞溪诗歌中的诸葛毫、鲤庭、桃梅讽答，都没有出现于欧阳修等人的试笔诗文，表明瑞溪与欧阳修等人的试笔诗没有交流关系。试毫二字是与欧阳修等人试笔诗文存在交流关系的唯一线索，但根据这一线索无法查出典据关系、典据范围。试笔是中国文学的常识，也是五山文学的常识。横川景三的《试笔诗唱和序》记载：

> 世有试笔诗也久矣，宋元以来，骚人墨客，唱和集中，比比有之。甚则虽吾方外之士，不能无斯作也。一初新年试笔，真净和人试笔是也。本朝丛林，雏僧髫童，元日必诗而试笔，如酌屠苏之酒也，所以祝岁也。……昔司马温公，居东都日，年尚少。公与耆英，结社赋诗。其序曰：“元丰五年正月。”盖千载佳话也。抑东山，古之东都也。少年，今之温公也。洛社风流，以唱以和，耆英之会，入图以传，呜呼盛乎？（横川景三，『拾遺』906）

横川景三以为宋元以来试笔诗“比比有之”，处处可见，这就超出了典据范围。但这并不妨碍认为试笔诗最初来自中国，交流关系是存在的，但没有特定试笔诗文本的交流关系，只有开放的常见关系。日本禅林的少年僧人每年元旦都要写试笔诗贺岁，并求高僧唱和，可见试笔诗是当时的常识。横川景三以为这种体制来自司马光等人的正月试笔诗，不管这种说法是否准确，试笔诗传入了日本，并发展为了一种诗歌类型。但这并不表明五山诗人的试笔诗，同司马光、欧阳修等人的试笔诗存在交流关系，五山

诗人从司马光等人的试笔诗中吸收的是试笔诗的一般特征，而不是从他们的特定文本中吸取需要的因素。其结果只能是在试笔诗的一般知识层面产生了交流关系，并创作了自己的试笔诗，特定文本之间没有出现交流关系。作为概念的试笔诗可以覆盖中日所有的试笔诗，但并不表明中日试笔诗的文本之间存在交流关系，也就无法确定典据关系或典据范围。这似乎与春、秋、风、雨等常用字词的交流关系完全相同，但实际上有所差异。春、秋、风、雨的汉字来自中国，但这些字词指称的自然事物并不来自中国。日本原本没有试笔诗，日本的试笔诗是通过交流才出现的，因而需要出注研究。

常见关系的交流形态不同于线性关系、网状关系，应当采用不同的研究方法。阅读书目丧失了有效性，因而可以采用总体研究的方法或源流研究的方法。这样的方法不必执着于试笔诗特定文本的交流关系，可以分别研究中日的试笔诗，从而呈现交流关系；也可以研究源流关系的流变，同样不必拘泥于特定文本的交流关系。常见关系作为研究对象的特征是自由的，研究方法也是自由的，这样可以自由地研究各种问题。如果研究试笔诗的基本问题，在注释中可以提供基本信息：五山试笔诗有哪些特征，有哪些重要的诗人，试笔诗究竟产生了怎样的作用等等。这是读者需要了解的信息，也是基于常识的问题。宋代之前试笔诗的产生与发展，宋元试笔诗兴盛的原因与类型，明清时期是否仍然存在试笔诗，又有怎样的变化与发展，诸如此类问题超出了瑞溪周凤试笔诗文本的交流关系范围，但这是试笔诗的概念、知识层面的交流关系问题。常见关系是开放的交流关系，阅读书目与一般书目没有差异，也就没有必要坚持使用阅读书目的原则，只要能够解决问题，可以自由使用各种书目，甚至是迟晚于校注文本的书目文献。

从法国学派的源流线性关系，到比较文学文献学的交流线性关系，再到网状关系与常见关系，交流关系的描述已经发生了颠覆性的变化。交流关系复杂多变，但比较文学研究史描述的文学关系只有一种，这种可能性是不存在的，显然不可能是事实。除了法国学派的源流关系之外，还存在其它三种交流关系，这应当更接近于文学关系的事实。这对于比较文学交流关系的研究有着重要的意义：一是需要反思与重新研究先行研究的个案。由于先行研究描述的交流关系只有源流线性关系，迄今为止都是将各种不同的交流关系全都描述为了源流线性关系，其中不免出现很多讹误，因而完全可能需要重新研究交流关系的个案。二是发现新的交流关系形态之后，必然影响未来的交流关系研究，应当考虑到交流关系的各种形态，不能将交流线性关系全部描述为源流线性关系，因此交流关系的研究很可能发生重要的变化。充分地调查文献，准确描述交流的不同事实形态，这样才能真正推进交流关系的研究。

注解【Notes】

①梵·第根说：“地道的比较文学最通常研究那些只在两个因子间的‘二元的’关系；这些因子或者是作品，或者是作家，或者是作品或人的集团：这些关系则是关于艺术作品的实质和内容的”（参见《比

较文学论》，戴望舒译，吉林出版集团 2009 年，第 138 页）。现今学界极少提及影响研究、平行研究，只是在教材中可以看到介绍而已。这是当前学术界的事实，但也掩盖了另一种事实：文学关系研究仍然是主要领域之一，只是并不一定以影响研究、平行研究为题。影响研究、平行研究似乎早已成为了早期的“古董”，与今天的学术没有多大关系，但这种印象并不正确。

②关于比较文学文献学可参看张哲俊：《寿星形象的流变与校勘、注释的纠缠：比较文学文献学示例》，《外国文学评论》第2期，2023年5月，第122—142页；张哲俊：《比较文学文献学：从潜在书目的网状关系再探文学交流关系研究》，《外国文学评论》第4期，2024年11月，第132—151页；张哲俊：《从日藏汉籍书目到比较文学文献学——不是为了纪念的纪念》，《中国比较文学》第1期，2024年1月，第224—241页；张哲俊：《比较文学文献学：五山文学唐风地名的来源与使用》，《广东社会科学》第5期，2024年9月，第153—173、287页等等。

③一条语词多点多线的网状关系是基本形态，一首诗歌是由复数的语词构成的，那么就可能存在复数的网状关系。复数的网状关系各自独立，也可以彼此交集。语境是不同语词产生交集的原因，特定语境的语词存在一定的关系，这样不同的网状关系也可以交集，形成更大的网状关系。大的网状关系比基本网状关系复杂，但仍然是可描述的，依旧是可以研究的对象。

④这不是特例，瑞溪《栖云斋图》无心出岫的用例也存在类似的交流形态：“无心出岫犹多叀，独爱高人不过溪”（参见瑞溪周鳳：『卧雲藁』，『五山文學新集』第五册，第 573 页）。阅读书目有用例，典源与典据用例、篇目为晋陶潜《陶渊明集・归去来兮辞》卷五：“云无心以出岫，鸟倦飞而知还”（参见陶渊明撰：《陶渊明集笺注》卷第五，袁行霈笺注，中华书局，2003 年，第 461 页）。《文选》卷四五、《艺文类聚》卷三六、《古今事文类聚别集》卷二五皆载，同为典据书目的范围。阅读书目又有连续四字相同的用例，宋方岳《秋崖集・山中其六》卷九：“无心出岫懒于云，生死交情一付君”（参见方岳撰：《秋崖诗词校注》卷二十，秦效成校注，黄山书社，1998 年，第 350 页）。此为典据，形成了线性关系，这样无心出岫出现了线性关系与网状关系共在的形态。

⑤理论上说典据范围应当提供所有阅读书目的清单，不应遗漏阅读书目，但实际上这种可能性几乎不存在：首先，一本别集的校注有数千条甚至数万条，难免会遗漏典据范围的书目。这样无法提供所有的交流信息，尽管遗憾，也很无奈。只要没有改变交流关系的性质，就不会造成严重问题。其次，阅读书目中存在佚书，不可能作为调查对象。《会翁录》《百田录》《三学古今杂集》等等书目已佚。

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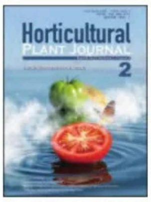

Review

The coordinated interaction or regulation between floral pigments and volatile organic compounds

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ABSTRACT

Floral color and scent are crucial for plant–environment interactions, especially in reproduction by attracting pollinators for fertilization. They also have wide applications in cosmetic, pharmaceutical, and nutraceutical industries. Plant pigments are typically classified as chlorophylls, flavonoids, carotenoids, and betalains, while volatile organic compounds (VOCs) are grouped as terpenes, phenylpropanoids/benzenoids, and fatty acid derivatives. Significant progresses have been made in understanding the biosynthesis and regulation of these floral pigments and VOCs. Despite differences in their biosynthetic pathways, floral pigments and VOCs are biochemically connected and exhibit synergistic interactions during flower development and in response to biotic and abiotic stresses, suggesting the existence of pleiotropic regulators or complex mechanisms co-regulating their biosynthesis. In this review, we summarize and outline the metabolite pathways mainly integrating flavonoids, carotenoids, terpenes, and phenylpropanoids/benzenoids. We also provide a series of scenarios illustrating the coordinated regulation of floral color and scent. Finally, we suggest areas for future research. We hope this review will spark interest in this research direction and stimulate further studies.

Keywords: Color and scent; Co-regulation; Pleiotropic regulators; Promoter analysis; Specialized metabolites

1. Introduction

Angiosperms, or flowering plants, comprise the most diverse group of land plants on Earth, with over 300 000 species known to date. They first appeared in the fossil record around 140 million years ago, and their rapid diversification and proliferation have been linked to the evolution of their unique reproductive structures, particularly flowers (Benton et al., 2022). Unlike ferns and conifers, which rely on wind or water to disperse their spores or seeds, respectively, angiosperms have evolved a more efficient means of reproduction through the use of flowers. Flowers contain both male and female reproductive structures, allowing for efficient pollination and fertilization, often facilitated by animal pollinators such as bees, butterflies, and birds. This efficient reproduction mechanism has allowed angiosperms to dominate terrestrial ecosystems, comprising the majority of plant biomass and providing the foundation of food webs (Chanderbali et al., 2016; Ramírez-Barahona et al., 2020).

One of the main functions of flowers is to interact with pollinators, driving the evolution of traits facilitating pollination, like

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color, scent, shape, and nectar production. These traits often co-occur in pollination syndromes, suites of traits adapted to particular pollinators (Raguso, 2004; Dellinger, 2020; Yang et al., 2023). Shifts in pollination syndromes have enabled angiosperm diversification by exploiting new ecological niches and geographic regions (Bradshaw and Schemske, 2003; Zufall and Rausher, 2004; Hoballah et al., 2007; Vandelook et al., 2019; Yarahmadov et al., 2020). Additionally, metabolites underlying flower color and scent can deter florivores and herbivorous insects, and affect predator attraction after florivore attack (Landi et al., 2015; Song et al., 2018b; Qiao et al., 2021a; Skaliter et al., 2022). For humans, flower color and scent are important ornamental traits that have been selectively bred in many flower crops. The commercial importance of these traits has led to development of numerous cultivars with unique colors and scents, widely used in floral industry for aesthetic appeal (Zhang et al., 2020; Caissard et al., 2022; Skaliter et al., 2022). In addition, natural components of flower color and scent are used across various industries, including cosmetics, pharmaceuticals, and nutraceuticals. While flower color and scent have been studied separately, growing interest exists in understanding potential links (Raguso and Weiss, 2015; Smith 2016; Wang et al., 2021), which is important not only for basic research in botany and ecology, but also practical applications in horticulture and floral industry. For example, when pursuing color diversity of ornamental plants and trying to prolong vase-life, flower scent seems to be weakened or degraded gradually (Dudareva and Pichersky, 2008; Hsiao et al., 2011; Amrad et al., 2016; Raguso, 2016; In et al., 2021). Further research could help develop new strategies for breeding ornamental plants with desirable color–scent combinations, minimizing trade-offs at the same time.

In this review, our aim is to summarize the molecular mechanisms underlying interaction between flower color and scent biosynthetic pathways, and explore potential co-regulation by transcription factors or other complex mechanisms. We also try to suggest future research directions in the end.

2. Components of floral pigment and fragrance

Flower pigments can be broadly classified into several groups, including chlorophylls, flavonoids, carotenoids, and betalains (Davies and Schwinn, 2010; Zhao and Tao, 2015). However, flowers with high chlorophyll levels are rare in the wild as green flowers can be difficult for pollinators to distinguish from the green leaf background (Narbona et al., 2021). Betalains are water-soluble pigments that provide a limited range of colors to flowers, but are mostly limited to *Caryophyllales* and mutually exclusive with anthocyanins, the most widely distributed pigments in plants (Narbona et al., 2021). Flavonoids, with their varied phenolic structures, are found in various plant tissues and organs, including anthocyanins, flavonols and flavones that confer yellow, red, purple and blue hues to flowers in most plants (Davies et al., 2012; Tohge et al., 2017; Wen et al., 2020; Narbona et al., 2021; Shen et al., 2022; Ge et al., 2023; He et al., 2023b). Hydrophobic carotenoids such as lycopene, carotene, and zeaxanthin, can be co-accumulated with flavonoids, usually giving yellow or red hues to many flowers (Yuan et al., 2015; Sun and Li, 2020; Sun et al., 2022). Flavonoids and carotenoids are more widely distributed and are often mentioned when referring to flower colors (Tanaka et al., 2008; Ng and Smith, 2016; Narbona et al., 2021; Yang et al., 2023).

The floral scent is a highly complex and dynamic mixture of volatile organic compounds (VOCs), which can be mainly classified into terpenes, benzenoids/phenylpropanoids and fatty acid derivatives based on their independent biosynthetic origins (Dudareva et al., 2013; Muhlemann et al., 2014; Qiao et al., 2021b). While components belonging to all three VOC classes can be detected in a single flower, the relative contents vary across different species. For example, chrysanthemum and peony cultivars tend to release more terpenes than benzenoids/phenylpropanoids or fatty acid derivatives, while petunia and rose (*Rosa damascene* and Chinese rose) are known for synthesizing benzenoids/phenylpropanoids in their flowers (Sun et al., 2015; Raymond et al., 2018; Song et al., 2018b; Luo et al., 2020; Huang et al., 2022b; Hou et al., 2023). Fatty acid derivatives are the major volatiles in the carnation flower fragrance signature and also dominant components detected as green leaf volatiles in a wide range of plant species (Schade et al., 2001). Overall, terpenes and benzenoids/phenylpropanoids usually represent the largest and second largest class of floral VOCs, respectively, compared to other VOCs such as fatty acid derivatives, sulphur- and nitrogen-containing compounds.

In this review, our primary focus is on color-related flavonoids and carotenoids, as well as scent-related terpenes and benzenoids/phenylpropanoids, to discuss the interaction and coordinated regulation between those floral pigments and VOCs.

3. The synthesis or pathway of main floral pigments and VOCs

Floral pigments and VOCs are rarely discussed together on a molecular basis. However, their biosynthetic pathways can be traced back to several precursors derived from primary metabolisms such as glycolysis, the tricarboxylic acid cycle and the pentose phosphate pathway (Behal et al., 2002; Zhang et al., 2017; Barja et al., 2021; Le et al., 2022). In fact, the main floral pigments and volatiles mentioned above can be broadly grouped into terpenoids (including carotenoids and volatile terpenes) and phenylpropanoids (including flavonoids and volatile benzenoids/phenylpropanoids) based on their common core backbones. Fig. 1 illustrates how terpenoid precursors, such as acetyl-CoA, pyruvate, and glyceraldehyde-3-phosphate, enter the mevalonate (MVA) pathway in the cytosol and the methylerythritol phosphate (MEP) pathway in plastids to produce the 5-carbon precursor isopentenyl diphosphate (IPP), which can be isomerized by isopentenyl pyrophosphate isomerase (IDI) to generate its allylic isomer dimethylallyl diphosphate (DMAPP). IPP and DMAPP are substrates for isopentenyl diphosphate synthases (IDSs), including geranyl diphosphate synthase (GPPS), farnesyl diphosphate synthase (FPPS), and geranylgeranyl diphosphate synthase (GGPPS), and serve as 5-carbon building blocks of all terpenoids. Terpene synthases (TPSs) then convert

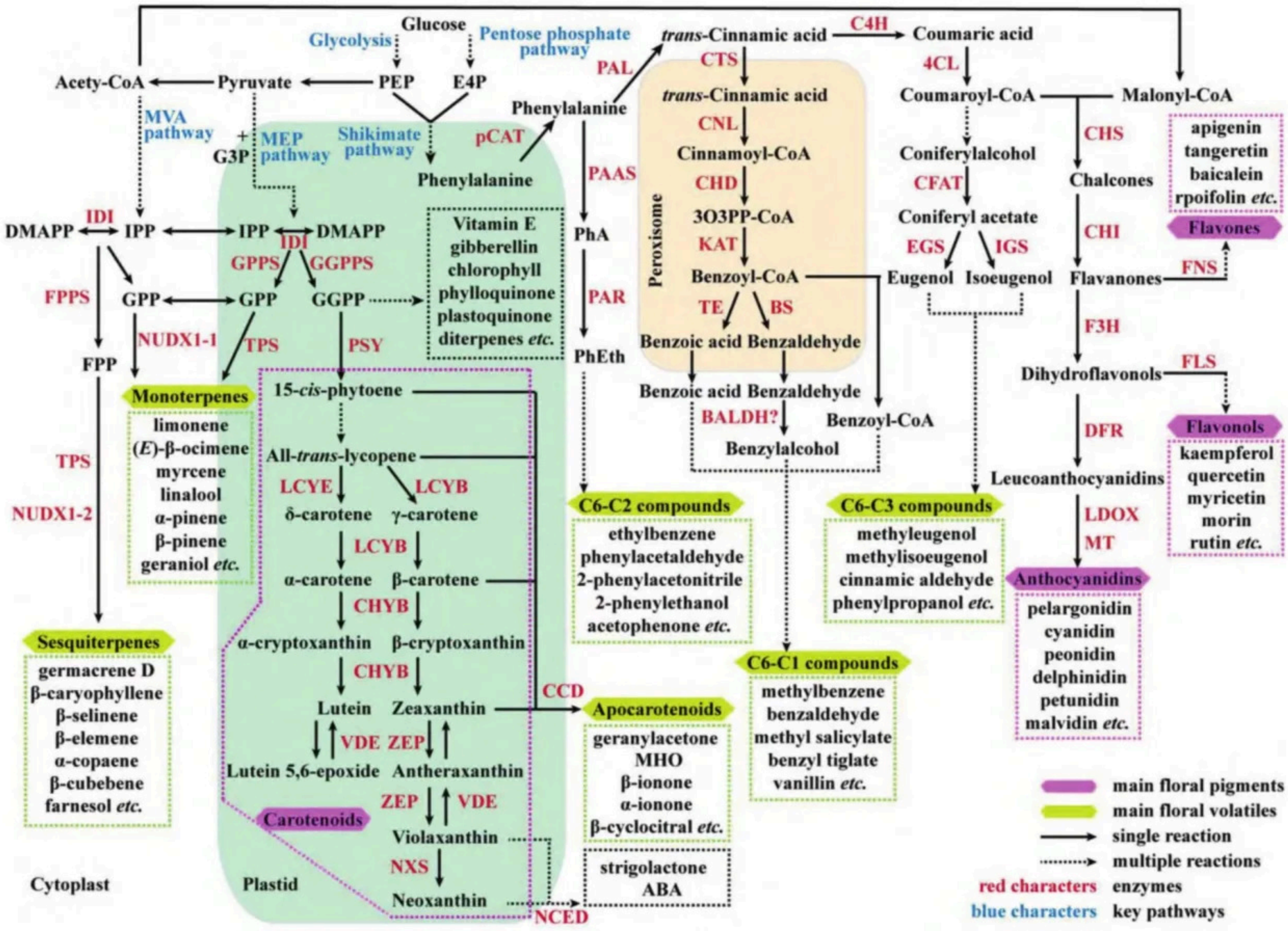

Fig. 1 Proposed biosynthetic network of the main floral pigments and VOCs in plants

Main floral pigments and VOCs are shaded by red and yellow background, respectively. Enzymes responsible for each biochemical reaction are shown in bold red. Characters with blue color indicate key metabolite pathways. Established single biochemical reactions are presented by solid black arrows, while unidentified steps or multiple reactions are shown by dashed arrows. Plastid and peroxisome are represented with green and orange colors. Abbreviations: IDI, isopentenyl diphosphate isomerase; GPPS, GPP synthase; FPPS, farnesyl diphosphate synthase; GGPPS, GGPP synthase; TPS, terpene synthase; NUDX, Nudix hydrolase; PSY, phytoene synthase; LCYE, lycopene ε-cyclase; LCYB, lycopene β-cyclase; CHYB, β-carotenoid hydroxylase; VDE, violaxanthin de-epoxidase; ZEP, zeaxanthin epoxidase; NXS, neoxanthin synthase; CCD, carotenoid cleavage dioxygenase; NCED, 9-cis-epoxy-carotenoid dioxygenase; pCAT, plastidial cationic amino acid transporter; PAAS, phenylacetaldehyde synthase; PAR, phenylacetaldehyde reductase; PAL, phenylalanine ammonia lyase; CTS, peroxisomal cinnamic acid/cinnamoyl-CoA transporter COMATOSE; CNL, cinnamate-CoA ligase; CHD, cinnamoyl-CoA hydratase/dehydrogenase; KAT, 3-ketoacyl thiolase; TE, thioesterase; BS, benzaldehyde synthase; BALDH, benzaldehyde dehydrogenase; C4H, cinnamate 4-hydroxylase; 4CL, 4-coumarate-CoA ligase; CFAT, coniferylalcohol acetyltransferase; EGS, eugenol synthase; IGS, isoeugenol synthase; CHS, chalcone synthase; CHI, chalcone isomerase; F3H, flavanone 3-hydroxylase; FNS, Flavone synthase; DFR, dihydroflavonol 4-reductase; LDOX, leucoanthocyanidin oxidase, MT, methyl transferase; FLS, flavonol synthase.

GPP to most C10 monoterpenes, FPP to most C15 sesquiterpenes, and GGPP to diterpenes. It is widely accepted that the diversity of plant terpenoids is largely attributed to TPSs, which have attracted special attention in both evolutionary and catalytic prospects over the last decade. Studies reveal that the TPS family has expanded several times due to gene duplications during plant evolution and has provided context for structure remodeling, differential expression, subcellular segregation, and neofunctionalization (Karunanithi and Zerbe, 2019; Jia et al., 2022). Although TPS has been extensively studied in many plants, fundamental knowledge regarding the origin and evolution of TPS in angiosperms, as well as the molecular or structural basis underlying functional differentiation of angiosperm-specific TPSs, remains in its infancy (Alicandri et al., 2020; Chen et al., 2020; Zhou and Pichersky, 2020; Jia et al., 2022; Bao et al., 2023).

Additionally, GGPP derived from MEP serves as a primary precursor for various terpenoids including carotenoids, tocopherols (vitamin E), gibberellins, chlorophylls, plastoquinones, and more (Hermanns et al., 2020; Barja and Rodriguez-Concepcion, 2021; Li et al., 2019a). Among these, carotenoids are crucial for photosynthesis and photoprotection, and impart vibrant orange, yellow or red colors to flowers. Interestingly, carotenoids can be cleaved or degraded by specific enzymes such as CCDs (carotenoid cleavage dioxygenases) or NCEDs (9-*cis*-epoxy-carotenoid dioxygenases), nonspecific enzymes, or non-enzymatic oxidation, producing a range of apocarotenoids, including phytohormones ABA and strigolactones, and a variety of volatiles with low odor thresholds, such as β-ionone, pseudoionone and 6-methyl-5-hepten-2-one (MHO), affecting the development, color, and scent of plants (Han et al., 2013, 2014; Yuan et al., 2015; Daruwalla and Kiser, 2020; Wang et al., 2023b).

The well-known shikimate pathway utilizes phosphoenolpyruvate (PEP) from glycolysis and erythritose 4-phosphate (E4P) from the pentose phosphate pathway to synthesize aromatic amino acids, including phenylalanine and tyrosine. Tyrosine can also be used for betalain synthesis in *Caryophyllales*, although we will not dwell on its discussion here. Phenylacetaldehyde synthase (PAAS) catalyzes phenylalanine to form phenylacetaldehyde, which is then converted to phenylethanol, providing the C6–C2 backbones related to phenylpropanoids. Alternatively, phenylalanine ammonia lyase (PAL) competes with PAAS to convert phenylalanine to cinnamic acid which can be used to synthesize benzenoid (C6–C1) skeletons, such as benzaldehyde, benzyl alcohol, and more, or transformed into coumaric acid for the formation of phenylpropanoids (C6–C3), lignins and flavonoids, and others. Recently, the benzaldehyde biosynthetic pathway in the model petunia was deciphered, and a peroxisomal heterodimeric enzyme involved in the β-oxidative pathway was found to be highly conserved among plants and contributed significantly to this process (Huang et al., 2022b).

It is widely accepted that flavonoid biosynthesis begins with coumaroyl-CoA and malonyl-CoA, converted by chalcone synthase (CHS) to produce chalcone. This is followed by cyclization by isomerase to form flavanone, further transformed into other flavonoids, like dihydroflavonols and flavones. Dihydroflavonols are key metabolites for producing flavonols and anthocyanins. The pathway has been extensively studied and described in numerous plants (Cheynier et al., 2013; Tohge et al., 2017; Wen et al., 2020). We won't delve into further detail here, instead depicting main floral pigments and volatiles together, using hub metabolites in metabolic fluxes.

The specific metabolic network appears much more complicated than originally proposed in Fig. 1 considering the presence of versatile modification enzymes, diverse structural components (Bureau et al., 2007; Lairson et al., 2008; Bontpart et al., 2015), non-canonical biosynthetic pathways (Dudareva et al., 2005; Magnard et al., 2015; Sun et al., 2016a), and transmembrane transportation of terpene precursor IPP or GPP (Magnard et al., 2015; Sun et al., 2016a). Here, we focus on the biosynthesis of geraniol and its derivative citronellol, primary constitutes responsible for characteristic rose scent or essential oil, for further discussion. Despite their importance, the intact biosynthetic pathway remains unknown and has been subject of much research. Although geraniol or citronellol is long considered as terpene synthase (TPS) product (Dong et al., 2013; Li et al., 2017b; Zhao et al., 2020a), no TPS has been found responsible for rose geraniol synthesis yet. Instead, the cytoplasmic NUDX1-1 enzyme has been identified participating in hydrolyzing GPP and forming geraniol in rose (Magnard et al., 2015). Moreover, NUDX1-2 also participates in farnesol biosynthesis by hydrolyzing FPP (Sun et al., 2020), indicating the earlier canonical TPS family isn't the only enzyme family catalyzing volatile terpene synthesis. Recent research has provided further insights into geraniol biosynthesis in rose flowers, with the identification of the cytosolic bifunctional RcG/FPPS1 enzyme clarifying the role of MVA-derived GPP (Conart et al., 2023). Geraniol is thought to be sequentially converted to several derivatives, including citral (a mixture of geranial and neral), citronellal, and citronellol, as verified by labeled isotopes (Iijima et al., 2014; Tan et al., 2018). Several enzymes such as GeDH (geraniol dehydrogenase), OPR (12-oxophytodienoate reductase), and GER (geranial reductase), are believed to be involved in these reactions (Chen et al., 2011; Sato-Masumoto and Ito, 2014; Iijima et al., 2016; Xu et al., 2017; Tan et al., 2018; Martinelli et al., 2023), but their orthologs in roses have yet to be uncovered. Additionally, the ambiguous molecular mechanism of citronellol pathway requires further investigation. For example, although the substrate of the cytoplasmic NUDX1 is cytoplasm-originated (Conart et al., 2023), the potential phosphatase following NUDX remains uncharacterized. It is also unclear how and where citronellol is converted from geraniol and whether cyclocitral, mainly generated from CCD-mediated cleavage of carotenoids, channels with geraniol or citronellol biosynthesis.

Contrary to most enzymes in specialized metabolite pathways, floral pigment and VOC synthesis has become more complex and challenging due to the involvement of heterodimeric enzymes like heterodimeric GPPS and benzaldehyde synthase, plus uncommon GPPS activity from cytosolic FPPS (Ueoka et al., 2020; Huang et al., 2022b; Conart et al., 2023; Song et al., 2023).

4. Synergistic regulation of floral color and scent is common among angiosperm plants

Plants typically rely on wind, water, insects, and birds for pollination, they can be classified as anemophilous, hydrophilous, entomophilous, or ornithophilous (Ackerman 2000; Klein et al., 2007; Ollerton et al., 2011). However, insect- and bird-pollinated plants are more efficient in terms of energy cost and reproductive success, thanks to their brightly colored or specially scented flowers that effectively attract pollinators (Delle-Vedove et al., 2011; Miller et al., 2011). As a result, floral pigments and VOCs work together to create an effective language mediating plant–pollinator interaction. Variations in floral pigments and VOCs are closely related to pollinator transition during plant evolution, and have been independently discovered and validated in several plant lineages, such as *Aquilegia* and monkeyflowers (Fenster et al., 2004; Hodges and Derieg, 2009; Shuttleworth and Johnson, 2010; Byers et al., 2014; Amrad et al., 2016; Liang et al., 2023). However, whether floral scent shows concerted changes with floral color has long remained unanswered for several reasons. Firstly, compared to floral color, floral scent is more difficult to define and appears more sensitive to various biotic or abiotic factors, making stable conclusions challenging. Secondly, due to earlier insensitive or uncommon analytical approaches and instruments, few researchers studied inter- or intraspecific floral scent variations during pollinator transitions within or between closely related species. Thirdly, previous plant–pollinator interaction studies focused mainly on single floral trait like color, with few researchers explicitly considering possible floral scent transitions accompanying color change. Finally, even if such synergistic changes were observed, their intrinsic interaction and underlying mechanism require further exploration. However, recent decades' technical and multi-subject developments including analytical chemistry, evolutionary biology, developmental biology and molecular biology, have increased attention to floral color and scent correlation at community, species, population, and individual levels (Mackay et al., 2009; Raguso and Weiss, 2015; Kantsa et al., 2017; Feng et al., 2021).

An increasing number of plant species exhibit synergistic changes in floral color and scent. For instance, studies suggest white- or pale-colored flowers tend to emit more VOCs than darker-colored ones across various species like rhododendron, orchid, rose, and carnation (Zuker et al., 2002; Huang et al., 2009; Campbell et al., 2010; Zhu et al., 2010; Delle-Vedove et al., 2011; Bendahmane et al., 2013; Dormont et al., 2014; Shaipulah et al., 2016; Yeon and Kim, 2020). Although floral pigments and VOCs are produced through distinct metabolic pathways, they share some precursors in the early stages. This interaction may result from metabolic flux diversion, leading to competitive linkage between floral color and scent. On the contrary, some studies also report inconsistent results in natural populations or engineered transgene lines (Salzmann and Schiestl, 2007; Oliva et al., 2015; Yeon and Kim, 2020), suggesting the relationship between floral color and scent is more complex and may be species or lineage-specific.

The variation in floral pigments and volatiles within individual plants or flowers is intriguing and often manifests as covariation, paralleling the flower's development. For instance, early-stage flower buds appear green due to high chlorophyll and carotenoid levels in plastids. As flower develops, chlorophyll degrades or bleaches, while carotenoids may remain stable or even increase in fully blooming flowers but decrease during floral senescence in some plants like petunias, chrysanthemums, and roses, in which CCDs cleaving carotenoids into volatile apocarotenoids like the aromatic β-ionone, pseudoionone and MHO (Simkin et al., 2004; Huang et al., 2009; Zhu et al., 2010; Chen et al., 2021). Another vital and widely accepted scenario during flower development is the change of floral color or scent after pollination, which functions as signals of floral reward, attracting pollinators to high-reward, fresh flowers and deterring them from old, low-reward ones (Sheehan et al., 2012; Kantsa et al., 2017; Larsson et al., 2021). Moreover, hormones like gibberellic acid (GA), abscisic acid (ABA), and ethylene, whether internal or exogenous, may be other factors regulating the fluctuation of floral color and scent (Kumar et al., 2008; Ravid et al., 2017; Khunmuang et al., 2019; Liu et al., 2020). Auxin is also reported to inhibit anthocyanin accumulation but promote terpene biosynthesis (Danova et al., 2012; Çakmakçõ et al., 2020; Wang et al., 2020a). Similarly, flavonols, the co-pigments of anthocyanins belonging to flavonoids, may alter scent compound biosynthesis by affecting auxin transportation (Teale et al., 2021). Furthermore, pigments and VOCs are among the tactics that plants employ in response to flexible environmental conditions. Consequently, environmental factors such as light, temperature, and humidity can concurrently fine-tune the display of flower color and scent (Hu et al., 2013; Ye and Zhong, 2022). Of particular note, these factors may not function alone but usually in an interactional or reciprocal regulation mode. For a more detailed discussion about proof or examples pertaining to the synergistic variations of floral pigments and VOCs, recent reviews can be referred to (Raguso and Weiss, 2015; Yeon and Kim, 2021; Kapoor et al., 2022).

Flower color and scent can largely be attributed to variations in metabolite fluxes, primarily resulting from fluctuations in the expression of structural genes. Next- and third-generation sequencing technologies have rapidly advanced, enabling integration of genome or transcriptome sequencing with metabolome analysis to investigate genes coordinating flower color and scent (Raymond et al., 2018; Yang et al., 2021b). However, there are still more intrinsic mechanisms that need to be deciphered, considering the intricate correlations between flower color and scent.

5. Some pleiotropic regulators could co-regulate the biosynthesis of floral pigments and VOCs

Transcription factors are proteins that cells use to turn specific genes on or off, or to fine-tune enzymatic activity by modulating gene expression levels. As a result, changes in flower color and scent are often attributed to pathway gene expression changes mediated by transcription factors. Increasingly, studies have identified regulators from multiple families that participate in the modulation of floral color or scent. We endeavor to summarize all characterized transcription factors involved in either color synthesis or scent formation. While regulators related to color have been extensively studied in various tissues, organs, and diverse plants, our focus is primarily on regulators that have been characterized specifically in flowers or have a direct impact on flower pigmentation. Remarkably, floral anthocyanin biosynthesis alone boasts over 100 characterized regulators, while floral carotenoid formation involves only around a dozen factors. In contrast, no regulators associated with betalain biosynthesis have been characterized in flowers as of yet (Table 1). Notably, of floral anthocyanin-related transcription factors, the MYB, bHLH, and WD40 families predominate, underscoring the canonical MBW (MYB-bHLH-WD40) complex's conserved role in regulating flower anthocyanin biosynthesis across plant lineages. Additionally, about 100 transcription factors have been characterized in governing terpenes and benzenoids/phenylpropanoids biosynthesis in plants (Table 2).

However, if we narrow our consideration to transcription factors specifically impacting floral VOCs, the number of such factors would markedly decrease. These regulators are predominantly associated with MYB, bHLH, WRKY, ethylene response factor (ERF/AP2), basic leucine zipper (bZIP), and NAC-type families. However, most regulators associated with volatile terpenes and benzenoids/phenylpropanoids biosynthesis are frequently examined in isolation, either within a single plant species or independently of other well-established regulators. This lacks consensus rules or mechanisms, unlike the well-defined MBW complex in anthocyanin regulation (Ding, 2023). In most cases, these regulators were thought to be quite specific

Table 1 Transcriptional factors involved in floral anthocyanin biosynthesis

Species	GeneFamily	Gene	Metabolite	Reference
Anthurium andraeanum (Hort.)	MYB	*MYB2*	Anthocyanin	Li et al. (2016a)
Antirrhinum majus	MYB	*Rosea1, Rosea2,* and *Venosa*	Anthocyanin	Schwinn et al. (2006); Shang et al. (2011)
	MYB	*MYB305, MYB340*	Anthocyanin	Moyano et al. (1996)
	MYB	*MYB308*	Anthocyanin	Tamagnone et al. (1998)
	bHLH	*DELILA, MUTABILIS, INCOLORATA I*	Anthocyanin	Albert et al. (2021), Goodrich et al. (1992), Martin et al. (1991)
	WD40	*WDR*	Anthocyanin	Albert et al. (2021)
	small RNAs	*sRNA*	Anthocyanin	Bradley et al. (2017)
Aristolochia fimbriata	MYB	*MYB114-like*	Anthocyanin	Muñoz-Gómez et al. (2021)
	bHLH	*TT8, GL3*		
	WD40	*TTG1*		
Cattleya hybrid 'KOVA'	MYB	*PAP1, PAP2*	Anthocyanin	Li et al. (2020a)
	MYB	*PCP1*	Carotenoid	Li et al. (2020a)
	MADS	*AP3, AGL6*		
Chrysanthemum morifolium	MYB	*MYB4, MYB5-1, MYB6, MYB7*	Anthocyanin	Hong et al. (2015), Hong et al. (2019), Liu et al. (2015b), Tang et al. (2022), Xiang et al. (2015)
		MYB1	Anthocyanin	Zhu et al. (2013)
	bHLH	*bHLH24*	Anthocyanin	Hong et al. (2015)
		bHLH2, bHLH2.1	Anthocyanin	Xiang et al. (2021)
	bZIP	*HY5-1,2,3,4*	Anthocyanin	Dong et al. (2020), Ohmiya (2018)
	GATA	*GATA4*	Carotenoid	Huang et al. (2022a)
Clarkia	MYB	*MYB1*	Anthocyanin	Martins et al. (2017)
Clarkia gracilis ssp. sonomensis	MYB	*MYB12, MYB6, MYB11*	Anthocyanin	Lin and Rausher, 2021
Dahlia pinnata (syn. variabilis)	bHLH	*IVS, DEL*	Anthocyanin	Ohno et al. (2011)
	MYB	*MYB1*		
	WD40	*WDR1*		
Dendrobium hybrids	MYB	*MYB2*	Anthocyanin	Li et al. (2017a), Wang et al. (2022), Wu et al. (2003)
	bHLH	*bHLH1*	Anthocyanin	Li et al. (2017a), Wang et al. (2022)
Freesia hybrida	MYB	*PAP1L1, MYB5, MYB27, MYBx*	Anthocyanin	Li et al. (2019c, 2020b, 2020c)
	bHLH	*TT8L, GL3L*	Anthocyanin	Li et al. (2016b)
	WD40	*TTG1*	Anthocyanin	Shan et al. (2019)
Gentiana triflora	MYB	*MYB1R1, MYB1R9*	Anthocyanin	Nakatsuka et al. (2013)
		MYB3	Anthocyanin	Nakatsuka et al. (2008)
	bHLH	*bHLH1*	Anthocyanin	Nakatsuka et al. (2008)
Gerbera hybrida	MYB	*MYB10, MYB1*	Anthocyanin	Elomaa et al. (2003), Laitinen et al. (2008), Zhong et al. (2020)
	bHLH	*MYC1*	Anthocyanin	Elomaa et al. (1998, 2003)
Gorteria diffusa	MYB	*MYBSG6*	Anthocyanin	Fattorini et al. (2023)
Hydrangea macrophylla cv. "Forever Summer"	MYB	*MYB114*	Anthocyanin	Peng et al. (2021)
	WER	*WER-like*		
	WDR	*WDR68*		
Iochroma loxense	MYB	*MYBL1*	Anthocyanin	Gates et al. (2018)
Ipomoea nil	MYB	*MYB1, MYB2, MYB3*	Anthocyanin	Morita et al. (2006)
	bHLH	*bHLH1, bHLH2, bHLH3*		
	WD40	*WDR1*		
Lilium spp.	MYB	*MYB6, MYB12, MYB12-Lat*	Anthocyanin	Lai et al. (2011), Yamagishi et al. (2010, 2012, 2014, 2018), Yamagishi (2020)
		MYB18	Anthocyanin	Yamagishi (2018)
		MYB5, MYB1	Anthocyanin	Yin et al. (2021)
		MYB15	Anthocyanin	Yamagishi (2016)
	bHLH	*bHLH1, bHLH2*	Anthocyanin	Nakatsuka et al. (2009)
	WD40	*WDR*	Anthocyanin	Dou et al. (2020)
Medicago truncatula	MYB	*WP1*	Carotenoid	Meng et al. (2019)
	bHLH	*TT8*		
	WD40	*WD40-1*		
Mimulus aurantiacus	MYB	*MYB2*	Anthocyanin	Streisfeld et al. (2013)
Mimulus guttatu	MYB	*MYB1, MYB2, MYB3*	Anthocyanin	Lowry et al. (2012)
Mimulus lewisii	MYB	*PELAN, NEGAN*	Anthocyanin	Yuan et al. (2014)
	bHLH	*ANbHLH1*		
	WD40	*WD40a*		
	MYB	*MIXTA-like R2R3 MYB*	Carotenoid	Yuan et al. (2013a)
	MYB	*RCP1*	Carotenoid	Sagawa et al. (2016)

Table 1 – (*continued*)

Species	GeneFamily	Gene	Metabolite	Reference
Mimulus lewisii and *Mimulus cardinalis*	MYB	*ROI1*	Anthocyanin	Yuan et al. (2013b)
	MYB	*LAR1*	Anthocyanin	Yuan et al. (2016)
	MYB	*PELAN*	Anthocyanin	Liang et al. (2022)
Mimulus. lewisii and *Mimulus. guttatus*	MYB	*NEGAN, RTO*	Anthocyanin	Ding et al. (2020a)
Mimulus lewisii and *Mimulus verbenaceu*	TPR	*RCP2*	Carotenoid	Stanley et al. (2020)
Narcissus tazetta L. var. chinensis Roem	MYB	*MYB2*	Anthocyanin	Anwar et al. (2018)
Narcissus tazetta L. var. *Chinensis* Roem	MYB	*MYB2*	Anthocyanin	Anwar et al. (2018)
Nelumbo Adans.	MYB	*MYB5*	Anthocyanin	Sun et al. (2016b)
	WD40	*TTG1*		
	MYB	*MYB108-like*	Anthocyanin	Liu et al. (2023b)
Nelumbo nucifera	MYB	*MYB5*	Anthocyanin	Liu et al. (2023a)
Oncidium Gower Ramsey	MYB	*MYB1*	Anthocyanin	Chiou and Yeh, 2008
Osmanthus fragrans	WRKY	*WRKY3*	Carotenoid	Han et al. (2016)
Paeonia suffruticosa	MYB	*MYB12*	Anthocyanin	Gu et al. (2019)
	bHLH	*bHLH*		
	WD40	*WD40*		
	SPL	*SPL2*	Anthocyanin	Luo et al. (2022)
Petunia hybrida	MYB	*AN2*	Anthocyanin	Quattrocchio et al. (1999) Hoballah et al. (2007)
	MYB	*DPL, PHZ, AN4*	Anthocyanin	Albert et al. (2011)
	bHLH	*AN1*	Anthocyanin	Spelt et al. (2000) Quattrocchio et al. (1993)
	bHLH	*JAF13*	Anthocyanin	Quattrocchio et al. (1998)
	WD40	*AN11*	Anthocyanin	De Vetten et al. (1997)
	MYB	*MYB27, MYBx*	Anthocyanin	Albert et al. (2014)
	WRKY	*PH3*	Anthocyanin	Verweij et al. (2016)
Phalaenopsis spp.	MYB	*MYB2, MYB11, MYB12*	Anthocyanin	Hsu et al. (2015)
	MYB	*MYBx1*	Anthocyanin	Fu et al. (2019)
	bHLH	*bHLH1-3*	Anthocyanin	Hsu et al. (2015)
Primula vulgaris	MYB	*MYB*	Anthocyanin	Li et al. (2019b)
	bHLH	*bHLH*	Anthocyanin	
Prunus mume	MYB	*MYBa1*	Anthocyanin	Zhang et al. (2017)
Prunus persica	MYB	*MYB10.2, MYB9, MYB17-20*	Anthocyanin	Zhou et al. (2016)
Ranunculus asiaticus L.	MYB	*MYB1*	Anthocyanin	Liu et al. (2021b)
Rhododendron latoucheae Franch	MYB	*MYB4*	Anthocyanin	Xiao et al. (2023)
	bHLH	*bHLH130, bHLH41, bHLH123*		
Rosa chinensis'Old Blush'	MYB	*MYB1*	Anthocyanin	He et al. (2023a)
	bHLH	*bHLH42, EGL1*		
	WD40	*TTG1*		
Rosa chinensis 'Semperflorens'cv. 'Slater's Crimson China'	MYB	*MYB114*	Anthocyanin	Li et al. (2022)
Rosa hybrida	MYB	*MYB10*	Anthocyanin	Lin-Wang et al. (2010)
	MYB	*MYB114a, MYB3b*	Anthocyanin	Yan et al. (2023)
	bZIP	HY5		
Rosa rugose	MYB	*MYB113*	Anthocyanin	Zou et al. (2018)
Sophora japonica L.	MYB, bHLH, WD40	PAP1, MYB111, MYB1b, MYBL2, TT8, TTG1	Anthocyanin	Gao et al. (2021); Guo et al. (2022)
Syringa oblata	MYB	*MYB*	Anthocyanin	Ma et al. (2022)
	bHLH	*bHLH*	Anthocyanin	
	WD40	*WD40*	Anthocyanin	
	ERF	*ERF*	Anthocyanin	
	WRKY	*WRKY*	Anthocyanin	
Torenia fournieri Lind. ex Fourn.	MYB	*MYB1*	Anthocyanin	Nishijima et al. (2013)

Table 2 Transcriptional factors involved in biosynthesis regulation of volatile compounds

Species	GeneFamily	Gene	Metabolite	Reference
Actinidia spp.	NAC	NAC1,2,3,4	Terpene	Nieuwenhuizen et al. (2015); Wang et al. (2022)
Amomum villosum Lour.	WRKY	WRKY61, WRKY28, WRKY40	Terpene	He et al. (2018)
Antirrhinum majus	MYB	MYB24	Terpene	Han et al. (2022a)
Aquilaria sinensis	JAZ	JAZ1	Terpene	Liao et al. (2023)
Arabidopsis thaliana	bZIP	HY5	Terpene	Michael et al. (2020)
	WRKY	WRKY40	Terpene	Alfieri et al. (2018)
	bHLH	MYC2, PIF	Terpene	Hong et al. (2012)
	bZIP	HY5	Terpene	Chenge-Espinosa et al. (2018)
	bHLH	PIF		
	MYB	MYB21	Terpene	Yang et al. (2020)
	bHLH	MYC2		
	MYB	MYB21, MYB24	Terpene	Tholl et al. (2005)
	MYB	PAP1	Benzenoid	Zvi et al. (2008)
	MYB	PAP1	Terpene	Zvi et al. (2012)
Artemisia annua	bHLH	MYC2	Terpene	Shen et al. (2016a)
	bHLH	MYC2	Terpene	Majid et al. (2019)
	bHLH	bHLH1	Terpene	Ji et al. (2014)
	bZIP	HY5	Terpene	Zhou et al. (2015)
	bZIP	bZIP1	Terpene	Zhang et al. (2015b)
	AP2/ERF	ERF1, ERF2	Terpene	Yu et al. (2012)
	AP2/ERF	ORA	Terpene	Lu et al. (2013)
	WRKY	WRKY1	Terpene	Ma et al. (2009)
	NAC	NAC1	Terpene	Lv et al. (2016)
Catharanthus roseus	MYB	BPF1	Terpene	Li et al. (2015a)
	WRKY	WRKY1	Terpene	Suttipanta et al. (2011)
	AP2/ERF	ORCA3	Terpene	van der Fits and Memelink (2000)
	AP2/ERF	ORCA2	Terpene	Li et al. (2013a)
	AP2/ERF	ORCA4, ORCA5	Terpene	Paul et al. (2017)
	Zinc Finger Proteins	ZCT1, ZCT2, ZCT3	Terpene	Pauw et al. (2004)
	bHLH	MYC2	Terpene	Zhang et al. (2011)
	bHLH	BIS1, 2	Terpene	Van Moerkercke et al. (2015, 2016)
	bHLH	bHLH	Terpene	Mertens et al. (2016b)
Chimonanthus praecox L.	bHLH	MYC2, bHLH13	Terpene	Aslam et al. (2020)
Chrysanthemum morifolium	WRKY	WRKY41	Terpene	Hu et al. (2023)
Cinnamomum osmophloeum	WRKY	WRKY	Terpene	Lin et al. (2014)
Citrus sinensis	AP2/ERF	ERF71	Terpene	Li et al. (2017b)
	AP2/ERF	CitAP2.10	Terpene	Shen et al. (2016b)
Cymbidium	MYB	MYB1	Benzenoid/ phenylpropanoid	Ramya et al. (2019)
Fragaria × *ananassa*	MYB	EOBII, MYB10	Benzenoid/ phenylpropanoid	Medina-Puche et al. (2015)
	DOF-type	DOF2	phenylpropanoid	Molina-Hidalgo et al. (2017)
Freesia hybrida	MYB	MYB21	Terpene	Yang et al. (2020)
	bHLH	MYC2	Terpene	
Gossypium arboreum	WRKY	WRKY1	Terpene	Xu et al. (2004)
Hedychium coronarium	ARF	ARF5	Terpene	Abbas et al. (2021a)
	MYB	MYBs	Terpene/ benzenoid/ phenylpropanoid	Abbas et al. (2021b)
	MYB	MYBs	Terpene	Ke et al. (2021)
	MYB	MYBs	Terpene/ benzenoid	Yue et al. (2015)
	bZIP	JAZ1	Terpene	Abbas et al. (2021b)
Lilium	MYB	MYB308, MYB330	Terpene	Guo et al. (2023)
	MYB	ODORANT1	Benzenoid/ phenylpropanoid	Yoshida et al. (2018)
	bHLH	MYC2	Terpene	Shi et al. (2018)
Litsea cubeba	WRKY	WRKY17	Terpene	Gao et al. (2023)
	MYB	MYB44	Terpene	Zhao et al. (2023)
Lavandula angustifolia	bHLH	MYC4	Terpene	Dong et al. (2022)
Lavandula × *intermedia*	MYB	MYB	Terpene	Sarker et al. (2019)
	bZIP	bZIP	Terpene	
	NAC	NAC	Terpene	
	GeBP	GeBP	Terpene	
	SBP	SBP-1	Terpene	

Table 2 – (*continued*)

Species	GeneFamily	Gene	Metabolite	Reference
Malus domestica	bHLH	*MYC2*	Terpene	Wang et al. (2020b)
	AP2/ERF	*ERF3*	Terpene	
	MYB	*MYB85*	Volatile esters	Li et al. (2023a)
	MYB	*MYB94*	Volatile esters	Li et al. (2023b)
	bHLH	*MYC2*	Volatile esters	Li et al. (2023a)
Medicago truncatula	bHLH	*TSAR1, TSAR2*	Terpene	Mertens et al. (2016a)
Mentha spicata	MYB	*MYB*	Terpene	Reddy et al. (2017)
	YABBY5	*YABBY5*	Terpene	Wang et al. (2016)
Nicotiana attenuata	WRKY	*WRKY3, WRKY6*	Terpene	Skibbe et al. (2008)
Oncidium hybrid	MYB	*CCA1*	Terpene	Yeh et al. (2022)
Oryza sativa	bZIP	*TGAP1*	Terpene	Okada et al. (2009)
	bZIP	*bZIP79*	Terpene	Miyamoto et al. (2015)
	bHLH	*DPF*	Terpene	Yamamura et al. (2015)
Osmanthus fragrans	MYB	*MYB21*	Terpene	Lan et al. (2023)
	bHLH	*MYC2*		
	bZIP	*JAZ3*		
	bHLH	*bHLH35*	Terpene	Han et al. (2022b)
	AP2/ERF	*ERF2*	Apocarotenoid	Han et al. (2022b)
	AP2/ERF	*ERF61*	Apocarotenoid	Han et al. (2019)
	WRKY	*WRKY19/36/84/139/7*	Terpene	Ding et al. (2020b)
Petunia hybrida	MYB	*ODO1, EOBI, EOBII, MYB4, PH4*	Benzenoid/ phenylpropanoid	van Moerkercke et al. (2011)
	MYB	*ODO1*	Benzenoid/ phenylpropanoid	Verdonk et al. (2005)
	MYB	*EOBII*	Benzenoid/ phenylpropanoid	Spitzer-Rimon et al. (2010)
	MYB	*MYB4*	Benzenoid/ phenylpropanoid	Colquhoun et al. (2010)
	MYB	*EOBI, EOBII*	Benzenoid/ phenylpropanoid	Chopy et al. (2023)
	MYB	*PH4*	Benzenoid/ phenylpropanoid	Cna'ani et al. (2015)
	AP2/ERF	*ERF6*	Benzenoid/ phenylpropanoid	Liu et al. (2017)
Phalaenopsis bellina	bHLH	*bHLH1, bHLH2, bHLH4, bHLH5, bHLH6*	Terpene	Chuang et al. (2017, 2018)
	MYB	*MYB22*	Terpene	
	bZIP	*bZIP1,4*	Terpene	
	AP2/ERF	*ERF1,9*	Terpene	
	NAC	*NAC1*	Terpene	
Picea glauca (white spruce) and *Pinus taeda* (loblolly pine)	MYB	*MYB4*	Terpene	Bedon et al. (2010)
Prunus mume	MYB	*MYBs*	Benzenoid/ phenylpropanoid	Zhao et al. (2017)
Prunus persica L. Batsch	bHLH	*bHLH1*	Terpene	Wei et al. (2021)
Rosa chinensis	WRKY	*WRKY70*	Terpene	Yu et al. (2022)
Salvia miltiorrhiza	bZIP	*bZIP1*	Terpene	Deng et al. (2020)
	WRKY	*WRKY1*	Terpene	Cao et al. (2018)
	AP2/ERF	*ERF128*	Terpene	Zhang et al. (2019)
Solanum lycopersicum	MYB	*MYB75*	Terpene	Gong et al., 2021
	Zinc finger-like	*EOT1*	Terpene	Spyropoulou et al. (2013)
	bHLH	*MYC1*	Terpene	Xu et al. (2018)
	bHLH	*MYC2*	Terpene	Spyropoulou et al. (2014)
	bHLH	*JIG1*	Terpene	Cao et al. (2022)
	WRKY	*WRKY73*	Terpene	Spyropoulou et al. (2014)
	NAC	*NAC-NOR*	Terpene	Gao et al. (2022)
	SCL	*SCL3*	Terpene	Yang et al. (2021a)
Tanacetum cinerariifolium	MYB	*MYB8*	Terpene	Zhou et al. (2022)
Taxus chinensis	WRKY	*WRKY1*	Terpene	Li et al. (2013b)
Taxus cuspidata	bHLH	*JAMYC1, 2, 4*	Terpene	Lenka et al. (2015)
Torreya grandis	bHLH	*bHLH95*	Terpene	Zhang et al. (2023a)
	bZIP	*bZIP44*		
Vitis vinifera	MYB	*MYB24*	Terpene	Zhang et al. (2023b)
Zea mays	AP2/ERF	*EREB58*	Terpene	Li et al. (2015b)
	bHLH	*MYC2*	Terpene	Ma et al. (2023)

in regulating particular metabolite pathways (Liu et al., 2015a; Ramya et al., 2017; Wu et al., 2022).

The number of structural genes is much higher than that of regulatory genes in a specific plant, which reflects the fact that different structural genes may share the same regulator (Tian et al., 2020). It is widely accepted that structural genes involved in the same metabolite pathway can be regulated by the same regulator. It is also possible that the structural genes belonging to different pathways, such as color and scent formations, can be regulated by the same regulator. Pleiotropic regulators or hormone-mediated regulators are reported to regulate distinct specialized metabolites (Bedon et al., 2010; Meng et al., 2019, 2023; Geng et al., 2020; Ni et al., 2023; Wang et al., 2023a; 2023b; Zhao et al., 2023a, 2023b; Zvi et al., 2012). Recent investigations have also highlighted the potential involvement of versatile regulators in concurrently governing pigments and VOCs (Raguso and Weiss, 2015; Yeon and Kim, 2020, 2021). For instance, over-expression of *Arabidopsis AtPAP1* in *Rosa hybrida* results in elevated levels of phenylpropanoid-derived color and scent compounds, alongside terpenoid scent compounds (Zvi et al., 2012). In petunia flowers, the synchronization of scent emission and pigmentation is finely regulated by the rhythmically expressed MYB transcription factor PH4, wherein PH4 affects petal pigmentation via vacuolar acidification in the early bud stage, and promotes scent emission during subsequent anthesis (Cna'ani et al., 2015). Furthermore, *Freesia* FhMYB21 has been identified as a participant in flavonol and terpene synthesis, while its orthologs in other plants exhibit diverse roles in response to the jasmonate or light signaling pathway (Shan et al., 2020; Yang et al., 2020; Zhang et al., 2021, 2023b; Chopy et al., 2023). The bZIP transcription factor AtHY5, involved in light signal transduction, has been reported to bind to *Arabidopsis* promoters of *AtPAP1*, *AtMYB12* and *AtTPS03*, thereby regulating anthocyanin, flavonol, and terpene biosynthesis, respectively (Stracke et al., 2010; Shin et al., 2013; Michael et al., 2020). DELLA protein is another factor co-regulating both anthocyanin and terpene pathways (Hong et al., 2012; Xie et al., 2016). Notably, the rose anthocyanin related RcMYB1 also plays a role in carotenoid and volatile aroma metabolic regulation (He et al., 2023a). In this context, we summarized reported transcription factors involved in both color and scent formation in Table 3. It is worth noting that the interplay between floral color and scent appears considerably more intricate than previously envisioned, warranting further in-depth investigation. In conclusion, the synergistic variation in floral color and scent can be attributed, at least partially, to the co-regulation by pleiotropic regulators.

6. Other possibilities explaining the synergistic variation of floral color and scent

In addition to the key enzymes represented by CCDs, which bridge the pigment and scent biosynthesis pathways, and the pleiotropic regulators mentioned earlier, there are other versatile genes that encode catalytic enzymes that can affect color and scent-related compounds simultaneously (Table 3). For instance, chalcone isomerase (CHI), which has long been known as an anthocyanin or flavonoid biosynthetic enzyme, also modulates

Table 3 Pleiotropic enzymes and transcription factors characterized to affect both plant pigmentation and scent

Species	Gene family	Gene	Metabolite	Reference
Brassica	CCD	*CCD*	Carotenoids	Zhang et al. (2015a)
Dianthus caryophyllus L.	F3H	*F3H*	Anthocyanin/Terpene/Benzenoid	Zuker et al. (2002)
Glycine max	CCD	*CCD*	Carotenoids	Gao et al. (2021)
Nicotiana attenuata	CHS	*CHS*	Anthocyanin/phenylpropenes	Kessler et al. (2008)
Osmanthu fragrans	CCD	*CCD*	Carotenoids	Chen et al. (2021)
Petunia hybrida	CCoAOMT	*CCoAOMT*	Anthocyanin/phenylpropenes	Shaipulah et al. (2016)
rosa damascena	CCD	*CCD*	Carotenoids	Huang et al. (2009)
Rosa rugosa.	BAHD	*ACT*	Anthocyanin/Terpene	Feng et al. (2021)
	GT	*GT5*		
Solanum lycopersicum	CHI	*CHI*	Anthocyanin/Terpene	Kang et al. (2014), Sugimoto et al. (2022)
Arabidopsis thaliana	SPL	*SPL9*	Anthocyanin/Terpene	Gou et al. (2011), Yu et al. (2014)
	bZIP	*HY5*	Anthocyanin/Terpene	Stracke et al. (2010), Shin et al. (2013), Michael et al. (2020)
	bHLH	*DELLA*	Anthocyanin/Terpene	Dombrecht et al. (2007), Xie et al. (2016)
	bHLH	*MYC2*	Anthocyanin/Terpene/Jasmonate	Dombrecht et al. (2007), Hong et al. (2012)
	MYB	*MYB21, MYB24*	Anthocyanin/Terpene	Yadav et al. (2012), Shan et al. (2020), Yang et al. (2020)
Freesia hybrida	MYB	*MYB21L1, MYB21L2*	Anthocyanin/Terpene	Yang et al. (2020) Shan et al. (2020)
	bHLH	*MYC2*	Anthocyanin/Terpene	Yang et al. (2020)
Ipomoea purpurea	MYB	*PAP1*	Anthocyanin/Terpene	Majetic et al. (2010)
Petunia hybrida	MYB	*PH4*	Anthocyanin/phenylpropenes	Cna'ani et al. (2015)
	MYB	*PAP1*	Anthocyanin/phenylpropenes	Zvi et al. (2008)
Rosa chinensis 'Old Blush'	SPL	*SPL9*	Anthocyanin/Terpene	Raymond et al. (2018)
Rosa hybrida	MYB	*MYB1*	Anthocyanin/Terpene	He et al., 2023a
	MYB	*PAP1*	Anthocyanin/Terpene	Zvi et al. (2012)
Solanum lycopersicum	MYB	*MYB75*	Anthocyanin/Terpene	Jian et al. (2019), Gong et al., 2021
Vitis vinifera L.	MYB	*MYB24*	Anthocyanin/Terpene	Zhang et al. (2023b)
	WRKY	*WRKY70*	Flavonol/Terpene	Wei et al. (2023)

terpenoid production in the glandular trichomes of tomato (Kang et al., 2014; Liu et al., 2021a). Carnation flowers with cream color morph produced by suppressing flavanone 3-hydroxylase (F3H) emit more methyl benzoate and 2-hydroxy methyl benzoate than reddish-orange basic cultivars (Zuker et al., 2002). The widely distributed glycosyltransferases have been characterized to transfer different sugar moieties to specialized metabolites, thus changing the color and scent by altering pigment stability and the volatility of VOCs (Song et al., 2018a; Chen et al., 2019; Zhao et al., 2020b). Additionally, the *Rosa rugosa* acetyltransferase gene encoding CoA geraniol/citronellol acetyltransferase is reported to participate in flavonoid, phenylpropanoid, and terpenoid biosynthesis, while anthocyanin glycosylation-related *GT5* is involved in both flavonoid and phenylpropanoid biosynthesis pathways (Feng et al., 2021). In Petunia, PhCCoAOMT1 catalyzes caffeoyl-CoA methylation to produce feruloyl CoA. Silencing PhCCoAOMT1 reduces eugenol but not isoeugenol. Down-regulating PhCCoAOMT1 activates the anthocyanin pathway through R2R3-MYBs PURPLE HAZE (PHZ) and DEEP PURPLE, with petunidin predominantly accumulating (Shaipulah et al., 2016). Although the aforementioned pleiotropic enzymes could co-regulate floral pigment and VOC biosynthesis, the descriptions have largely been examined within individual species. Establishing a universal framework requires more comprehensive research, especially encompassing diverse plant species.

Pleiotropic effects can also arise from quantitative trait loci (QTL) controlling floral traits. Flower color and scent can be influenced by multiple QTLs, many of which are pleiotropic, affecting multiple floral traits (Smith 2016). However, the co-localization of flower color and scent traits within the same QTL does not necessarily prove pleiotropy as a single QTL can encompass many genes and the observed influence on multiple traits could be due to linked genes (Hermann et al., 2013). Combining fine-scale mapping and identifying candidate genes expedites finding genuinely pleiotropic genes underlying pleiotropic QTL (Smith, 2016).

Post-transcriptional mechanisms such as differential splicing (Wang et al., 2022) and the involvement of regulatory RNAs (Raymond et al., 2018; Yang et al., 2021b; Yue et al., 2022), introduce an additional layer of control for modulating enzyme activity and finely adjusting pigment or scent production (Sun and Li, 2020). Moreover, post-translational regulation, which includes processes such as phosphorylation and sumoylation offers additional potential strategies for the coordinated regulation of color and scent (Kersten et al., 2015; Yang et al., 2022; Khan and Abbas, 2023). Additionally, the orchestration of metabolic flux through multi-

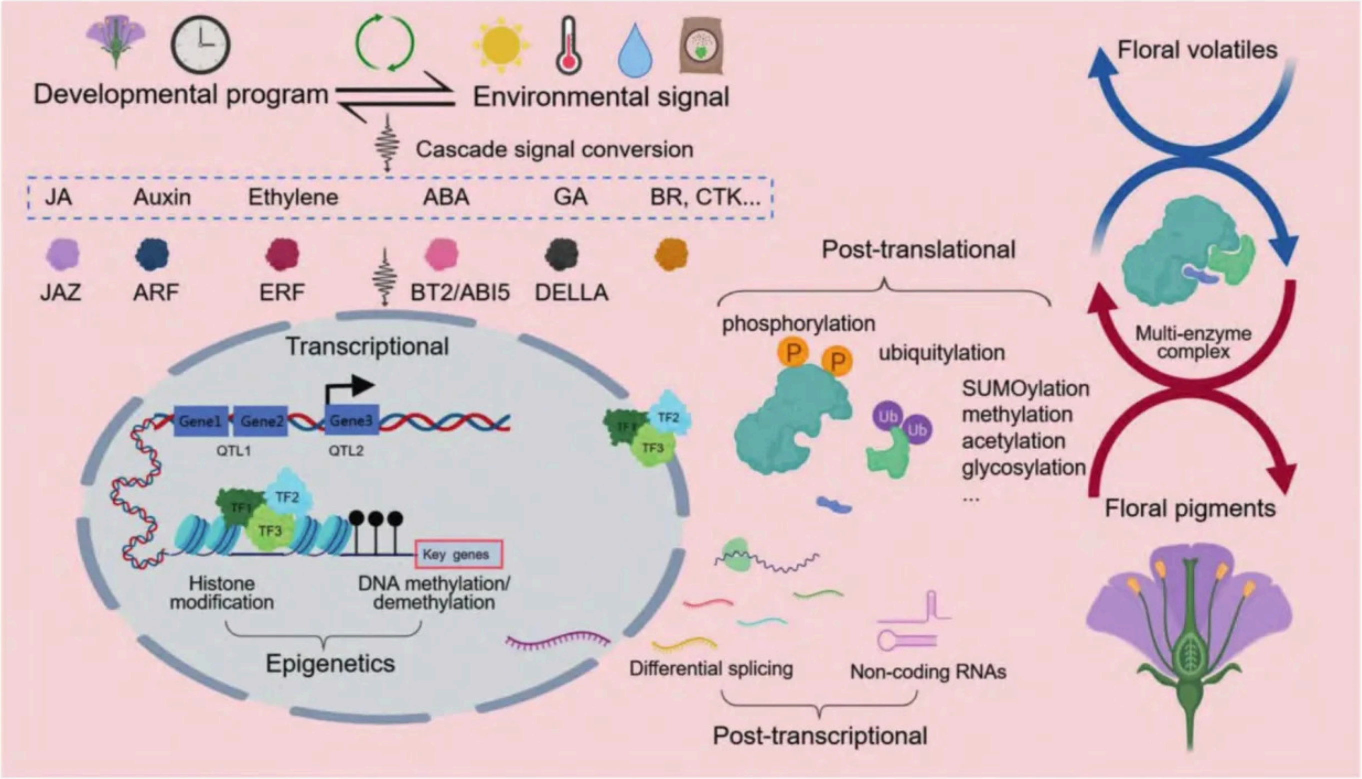

Fig. 2 Hierarchical regulation of floral pigments and floral volatiles

Floral pigments and floral volatiles are regulated by signals including developmental program and environmental cues, which could be transduced to nucleus by various hormones. These signals converge at the level of transcription factors to regulate gene expression. In addition, the transcription of pathway genes or the activities of key enzymes are regulated at differential levels. Epigenetic regulations represented by histone modification and DNA methylation/demethylation control gene expression. Differential splicing and non-coding small RNAs provide post-transcriptional regulations. Post-translational regulations examplied by protein modification and enzyme complex play critical roles in controlling metabolic pathway activity and fine-tune product production.

enzyme complexes presents another avenue for exploring the co-regulation of these floral traits (Camagna et al., 2019; Grabsztunowicz et al., 2017; Lloyd et al., 2017; Qiao et al., 2021a; Stanley and Yuan, 2019; Waki et al., 2020; Yu et al., 2023b). Furthermore, epigenetic mechanisms that integrate DNA methylation and histone modification are also potential mechanisms underlying the coordination and crosstalk between floral color and scent (Yuan et al., 2021; Tang et al., 2022; Yu et al., 2023a).

In summary, the interplay of hormone-mediated developmental and environmental signals, orchestrated by the actions of transcription factors, structural enzymes, major QTLs, as well as post-transcriptional and post-translational controls, and influenced by epigenetic modifications, collectively contribute to the diverse variations in flower color and scent observed in plants (Fig. 2).

7. Future prospect

Floral scent research has become an enriched area in horticulture and plant science in recent years. Significant progress has been made in understanding the biosynthesis and regulation of floral scent compounds, as well as their new functions over the past several decades. While recent technological advances have greatly aided this progress, there is still a long way to go to systematically clarify the mechanisms underlying the diversity of floral scent compounds, or even to catch up with our understanding of floral color molecules. The limited knowledge of floral scent formation and regulation has resulted in the underlying coordinated mechanisms being overlooked for a long time. As a result, various outstanding questions still remain to be addressed and interpreted.

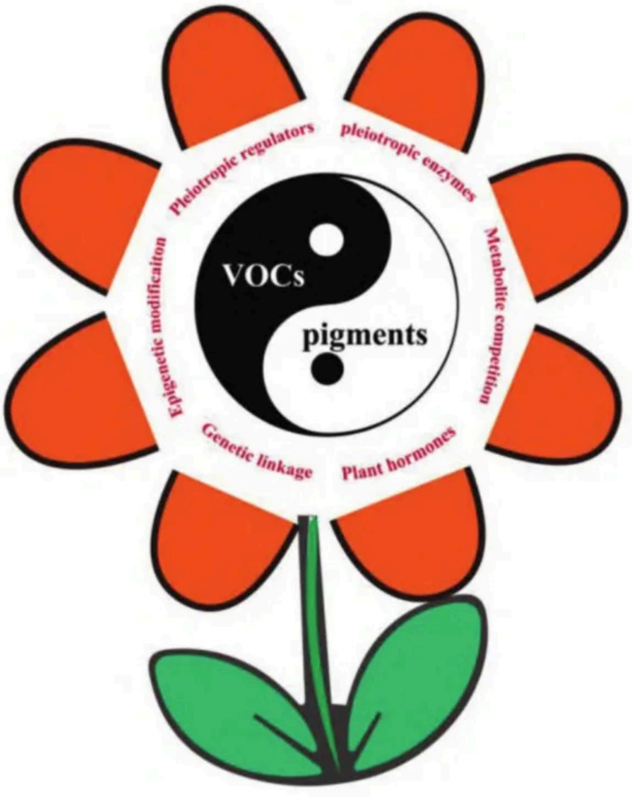

Fig. 3 Proposed schema interpreting the correlation between floral pigments and volatile organic compounds (VOCs)
The possible crosstalk and coordinated regulation between floral pigments and volatile organic compounds can be interpreted in the following aspects: pleiotropic regulators and enzymes, metabolic flux competition, plant hormone mediated regulation, genetic linkage, and epigenetic modification.

The identification and characterization of pathway genes involved in intrinsic metabolism, especially VOCs, continues to be a focus area of research. Although the main metabolic pathway is well understood, it is still unclear whether there is potential interflow or exchange of intermediate products, or whether alternative pathways exist. In addition, knowledge about the late modifications of color and scent molecules by modifying enzymes, such as cleavage, glycosylation, methylation, phosphorylation, and acylation, remains limited (Cao et al., 2023). The final pigments or VOCs should be localized to specific organelles or secreted into the air, but solid evidence is needed to understand the balance or interaction between compound synthesis and final floral coloration or aroma. Moreover, whether the enzymes or pathways that have been identified in specific species function in the same or similar ways across plant species is another fascinating question. While increasing studies suggest potential correlations between floral pigments and VOCs, the coordinated regulation of these biosynthetic pathways, how developmental and/or abiotic cues trigger coordination, and how plants evolve these capabilities remain unsolved mysteries that need further investigation. Although some transcription factors have been shown to regulate color and scent pathway genes or enzymes, gaps remain about their *bona fide* functions, functional conservation, interrelation, and how they respond to signaling pathways. Without a doubt, there must exist a highly intricate network within flowers that integrates all conceivable factors to finely regulate both color synthesis and scent formation (Fig. 3).

The advent of high-throughput screening technologies has opened the way to a new era of biological research. With an ever-growing number of multi-omics data integrating genome, transcriptome, and metabolome analyses based on either natural or artificial hybrid populations, we can gain more comprehensive insights into studying the molecular mechanisms behind flower color and scent. A meaningful model with an efficient genetic transformation system will dramatically broaden our understanding on the aforementioned questions.

Declaration of competing interest

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

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数学

MATHEMATICS

系统科学与数学
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一类平面非线性系统的稳定性研究*

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摘要　受平面线性系统的Routh-Hurwitz稳定性判据的启发, 本文研究了一类含未知参数的平面非线性系统的稳定性问题. 基于齐次系统理论, 运用李亚普洛夫方法和特解方法, 本文分析了系统的未知参数在满足各类条件时系统的稳定性, 并得到了一些充分条件和充分必要条件. 本文所采用的特解方法, 能有效地运用在系统的不稳定性分析上, 这丰富了非线性系统的稳定性分析方法. 此外, 本文所得到的结果可以被用在一些非线性系统的控制器设计上面, 文章给出了具体的实例来说明这一点.

关键词　平面非线性系统, 稳定性, 特解法, 李亚普洛夫函数.

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Study on stability of a class of planar nonlinear systems

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Abstract　Inspired by the Routh-Hurwitz stability criterion for planar linear systems, we investigate in this paper the stability of a class of planar nonlinear systems with unknown parameters. Drawing upon the framework of homogeneous system theory, we study the stability of a nonlinear system, which is inherently a homogeneous system, under various conditions of unknown parameters. The analysis employs both Lyapunov's method and the particular solution method to derive insights into the system's stability characteristics. As a result, several sufficient conditions, and necessary and sufficient conditions for stability are derived. The particular solution method adopted in this paper can be effectively applied to analyze the instability of the system, thereby enriching the methods available for the stability analysis of nonlinear systems. Furthermore, the results obtained in this paper have practical applications in the controller design of certain nonlinear systems. To demonstrate

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this, specific examples are provided to illustrate how the results can be utilized in practice.

Keywords planar nonlinear system, stability, special solution method, Lyapunov function.

1 引言

非线性系统是一类非线性动态微分方程. 这种系统被广泛用于描述各种实际系统和物理系统, 如图像处理、电路分析、热过程等. 非线性系统特性的分析常常是复杂的不确定的, 在一定条件下比线性系统复杂得多, 会产生突变、分岔、混沌等现象. 近年来, 非线性系统的稳定性引起了广泛地关注, 并出现了大量的理论结果[1, 2]. Ooba[3] 研究了一类二维 (2-D) 离散动力系统的渐近稳定性. 对于p阶非线性控制系统, Lin 等[4]提出了加幂积分器 (AAPI) 的技术, 并设计了高增益非线性反馈控制器来实现系统的全局镇定. Zhu 等[5] 研究了一类非线性系统在临界情况下的局部渐近稳定性, 给出了系统局部渐近稳定的一个充要条件. Li 等[6] 提出了时变时滞系统有限时间稳定性的Lyapunov条件. Lai 等[7] 提出了系统参数与拓扑参数具有明显的相关性, 并且这种相关性会影响系统的稳定性, 合理调整系统参数可以显著改善系统的稳定性条件. 在非线性系统的稳定性方面, 虽然已经提出了一些方法并取得了相应的进展[8], 但由于缺乏系统性和建设性的理论工具, 非线性系统的稳定性分析仍然是一个具有挑战性的问题.

随着齐次非线性理论的发展, 许多学者致力于运用这一理论研究非线性系统的控制问题. Du 等[9]指出了齐次条件在非线性系统分析中起着至关重要的作用, 并且齐次非线性系统比一般非线性系统有更多的优点. Liang 等[10] 研究了齐次非线性正切换系统的稳定性. 如果将齐次非线性理论应用到非线性系统的稳定性分析中, 它可以丰富已有的分析非线性系统的稳定性方法, 因此将齐次非线性理论应用到非线性系统的研究中是非常有意义的. 众所周知, 线性系统具有许多特殊而有趣的属性, 由于非线性系统的广泛应用, 我们自然而然考虑的是平面非线性系统的稳定性条件与线性系统稳定性条件之间是否有着相关的联系[11]. 基于以上讨论, 本文研究一类平面非线性系统的稳定性, 试图将平面线性系统稳定性理论扩展到这类非线性系统中.

20世纪60年代, Richardson[12]提出了一系列军备竞赛的正线性动力学模型系统, 它是线性动态系统在社会系统研究中最早的综合应用之一. 如果期望军备竞赛模型能够反映更加复杂多样情况下的军备竞赛, 那么需要考虑比经典Richardson 模型更为复杂的模型，此时非线性项的引入成为必然[13]. 因此, 有必要寻找有效的方法来分析与军备竞赛系统对应的非线性模型, 基于此, Zou 等[14]研究了一类平面齐次非线性正系统的稳定性, 将平面线性正系统的稳定性理论推广到了平面齐次非线性正系统中. 此外, Zou 等[15]进一步研究了齐次度为0的平面齐次非线性系统的稳定性. 由于文献 [14] 和 [15] 的系统模型分别满足一定的约束条件, 因此, 将文献 [14] 和 [15] 的理论结果运用到一般的平面齐次非线性系统中时, 这些结果具有局限性. 例如, 对

于神经网络模型[16], 我们无法直接借助文献[14] 和[15]的结果来判断其稳定性. 因而有必要进一步探讨一般的平面齐次非线性系统的稳定性.

本文基于平面线性系统的稳定性条件, 分析了一类平面非线性系统的稳定性问题. 本文的主要内容如下: 首先, 我们对本文研究的系统进行了明确的阐述, 并且给出了一些基本定义、基本定理和有用的引理. 然后给出了本文的主要研究结果, 即系统中的未知参数满足不同条件时系统的稳定性情况, 本文综合运用了特解法和李亚普诺夫法予以证明. 紧接着, 给出了一些具体实例来验证文中得到的结果, 最后是本文的总结.

2 研究模型与预备知识

考虑平面非线性系统

$$\begin{cases} \dot{x}_1(t) = (a_1x_1(t) + a_2x_2(t))^p, \\ \dot{x}_2(t) = (a_3x_1(t) + a_4x_2(t))^q, \end{cases} \tag{2.1}$$

其中$x = (x_1\, x_2)^T$是状态向量, p, q为奇数, a_1, a_2, a_3, a_4为未知参数且满足$a_1a_4 - a_2a_3 \neq 0$. 当$p = q = 1$ 时, 非线性系统退化为线性系统$\dot{x_1} = a_1x_1 + a_1x_2$, $\dot{x_2} = a_3x_1 + a_4x_2$, 其渐近稳定的充要条件为$a_1, a_2, a_3, a_4$满足$a_1 + a_4 < 0$, $a_1a_4 > a_2a_3$[17, 18]. 当$(p, q) \neq (1, 1)$时, 非线性系统的稳定性如何呢?

定义2.1[19] 已知$f_i : \mathbb{R}^n \to \mathbb{R}$, $i = 1, 2, \cdots, n$, 如果存在实数$\tau \in \mathbb{R}$及$r_i > 0, i = 1, 2, \cdots, n$, 使得

$$f_i(\varepsilon_1^r x_1, \cdots, \varepsilon_n^r x_n) = \varepsilon^{\tau + r_i} f_i(x_1, \cdots, x_n) \tag{2.2}$$

对任意的$(x_1, x_2, \cdots, x_n)^T \in \mathbb{R}^n$ 和$\varepsilon > 0$都成立, 则称$f = (f_1, f_2, \cdots, f_n)^T$ 为齐次系统, 其中τ 称为系统的齐次度, r_i 为x_i 的权.

齐次系统是指描述系统的向量场具有齐次性, 向量场的齐次性保证了解空间与解空间中的单位闭球存在映射关系, 因而整个解空间可以看作是单位闭球的膨胀. 齐次系统具有比一般非线性系统更多的优点, 齐次系统的稳定性可以借助齐次度刻画. 将齐次性应用到非线性系统的稳定性分析中，能够拓展非线性系统的稳定性分析方法.

由(2.1)和(2.2)得, 当$p = q$ 时, 系统(2.1)是一个齐次非线性系统, 且$r_1 = r_2$, $\tau = r_1(p - 1)$. 受平面线性系统渐近稳定的充要条件的启发, 基于齐次系统理论, 本文在齐次性条件下研究系统(2.1)的稳定性, 具体的系统模型如下

$$\begin{cases} \dot{x}_1(t) = (a_1x_1(t) + a_2x_2(t))^p, \\ \dot{x}_2(t) = (a_3x_1(t) + a_4x_2(t))^p, \end{cases} \tag{2.3}$$

其中$x = (x_1\, x_2)^T$是状态向量, p为奇数, a_1, a_2, a_3, a_4为未知参数且满足$a_1a_4 - a_2a_3 \neq 0$. 在给出具体结果前, 我们先给出一些预备的定理以及引理.

定理2.2 给定一个非线性系统$\dot{x} = f(x), x \in \mathbb{R}^n$, 其中$f(x)$ 是李普希兹连续的且$f(0) = 0$. (i) 如果存在一个连续可微的函数$V(x)$, 使得$V(x)$ 正定且对任意$x \neq 0$有$\dot{V}(x) := \frac{\partial V(x)}{\partial x} f(x) < 0$, 则称系统是渐近稳定的[20]. (ii) 如果存在一个连续可微

的函数 $V(x)$, 使得 $V(x)$ 正定, $\dot{V}(x) := \frac{\partial V(x)}{\partial x} f(x) \leqslant 0$ 且 $\dot{x} = f(x)$ 和 $\dot{V}(x) = 0$ 的解都为 $x = 0$, 则称系统是渐近稳定的[21].

定理2.3[22] $x = 0$ 是 $\dot{x} = f(x), x \in \mathbb{R}^n$ 的不稳定平衡点, 如果存在一个连续可微的函数 $V(x)$ 使得: (i) 原点是集合 G 的一个边界点, 其中 $G = \{x \in \mathbb{R}^n \mid V(x) > 0\}$, (ii) 存在 $x = 0$ 的一个邻域 U, 对任意的 $x \in U \cap G$, 有 $\dot{V}(x) > 0$.

引理2.4[9, 23] 对于任意正整数 m, n 和实值函数 $\gamma(x, y) > 0$, 下列不等式成立:

$$|x^m y^n| \leqslant \frac{m}{m+n} \gamma(x, y) |x|^{m+n} + \frac{n}{m+n} \gamma^{-\frac{m}{n}}(x, y) |y|^{m+n}.$$

引理2.5[14] 考虑一个连续可微函数 $V(x) = \frac{p}{p+1} x_1^{\frac{p+1}{p}} + a x_1 x_2 + \frac{b}{p+1} x_2^{p+1}$, 其中 $b > 0$, p 为正奇数. 如果 $a^{p+1} < b$, 则 $V(x)$ 是正定的.

3 主要结果

考虑系统 (2.3), 由于 $a_1 a_4 - a_2 a_3 \neq 0$, 对其作可逆线性变换 $z_1 = a_1 x_1 + a_2 x_2$, $z_2 = a_3 x_1 + a_4 x_2$, 得到系统

$$\begin{cases} \dot{z}_1 = a_1 z_1^p + a_2 z_2^p, \\ \dot{z}_2 = a_3 z_1^p + a_4 z_2^p. \end{cases} \tag{3.1}$$

文献 [16] 介绍了一种新的神经网络模型, 即 $\dot{z}_1 = -0.1 z_1^3 + 2 z_2^3$, $\dot{z}_2 = -2 z_1^3 - 0.1 z_2^3$, 值得注意的是, 系统 (3.1) 是这种模型的一般形式. 由于系统 (2.3) 与系统 (3.1) 等价, 代替系统 (2.3), 下面我们分析系统 (3.1) 的稳定性, 试图丰富非线性系统的稳定性理论, 并为深度神经网络的建模提供思路.

引理3.1 考虑非线性系统 (3.1). 定义

$$f(\lambda) = a_2 a_3 - \left(a_1 + \frac{\lambda}{p-1}\right)^{\frac{1}{p}} \left(a_4 \left(a_1 + \frac{\lambda}{p-1}\right)^{\frac{p-1}{p}} + \frac{\lambda}{p-1} a_2^{\frac{p-1}{p}}\right). \tag{3.2}$$

如果 $f(\lambda) = 0$ 存在一个实根, 则系统 (3.1) 存在一个特解.

证 当 $(a_2, a_3) = (0, 0)$ 时, $\lambda = (1-p) a_1$ 是 (3.2) 的一个实根. 易得

$$\begin{cases} z_1(t) = ((1-p) a_1 t + c_1)^{-\frac{1}{p-1}}, \\ z_2(t) = ((1-p) a_4 t + c_2)^{-\frac{1}{p-1}}, \end{cases} \tag{3.3}$$

是 (3.1) 的一个解, 其中 c_1, c_2 为正常数.

当 $(a_2, a_3) \neq (0, 0)$ 时, 不失一般性, 设 $a_2 \neq 0$, 若 λ^* 是 $f(\lambda) = 0$ 的一个实根, 则

$$\begin{cases} z_1(t) = -(\lambda^* t + c)^{-\frac{1}{p-1}}, \\ z_2(t) = \left(\dfrac{a_1 + \frac{\lambda^*}{p-1}}{a_2}\right) (\lambda^* t + c)^{-\frac{1}{p-1}}, \end{cases} \tag{3.4}$$

是系统 (3.1) 的一个解, 其中 c 是任意正常数. 由

$$f(\lambda^*) = a_2 a_3 - \left(a_1 + \frac{\lambda^*}{p-1}\right)^{\frac{1}{p}} \left(a_4 \left(a_1 + \frac{\lambda^*}{p-1}\right)^{\frac{p-1}{p}} + \frac{\lambda^*}{p-1} a_2^{\frac{p-1}{p}}\right) = 0$$

得$-\frac{\lambda^*}{p-1}\left(\frac{a_1+\frac{\lambda^*}{p-1}}{a_2}\right)^{\frac{1}{p}}=a_4\left(\frac{a_1+\frac{\lambda^*}{p-1}}{a_2}\right)-a_3$. 进而可以验证(3.4)式满足

$$\begin{aligned}\dot{z}_1(t)&=\frac{\lambda^*}{p-1}(\lambda^*t+c)^{-\frac{p}{p-1}}=a_1\left(-(\lambda^*t+c)^{-\frac{p}{p-1}}\right)+a_2\left(\frac{a_1+\frac{\lambda^*}{p-1}}{a_2}\right)(\lambda^*t+c)^{-\frac{p}{p-1}}\\&=a_1\left(-(\lambda^*t+c)^{-\frac{1}{p-1}}\right)^p+a_2\left(\left(\frac{a_1+\frac{\lambda^*}{p-1}}{a_2}\right)^{\frac{1}{p}}(\lambda^*t+c)^{-\frac{1}{p-1}}\right)^p\\&=a_1z_1^p(t)+a_2z_2^p(t)\end{aligned}\tag{3.5}$$

和

$$\begin{aligned}\dot{z}_2(t)&=-\frac{\lambda^*}{p-1}\left(\frac{a_1+\frac{\lambda^*}{p-1}}{a_2}\right)^{\frac{1}{p}}(\lambda^*t+c)^{-\frac{p}{p-1}}=\left(a_4\left(\frac{a_1+\frac{\lambda^*}{p-1}}{a_2}\right)-a_3\right)(\lambda^*t+c)^{-\frac{p}{p-1}}\\&=a_3\left(-(\lambda^*t+c)^{-\frac{1}{p-1}}\right)^p+a_4\left(\left(\frac{a_1+\frac{\lambda^*}{p-1}}{a_2}\right)^{\frac{1}{p}}(\lambda^*t+c)^{-\frac{1}{p-1}}\right)^p\\&=a_3z_1^p(t)+a_4z_2^p(t).\end{aligned}\tag{3.6}$$

由(3.5)和(3.6)得(3.4)是系统(3.1)的一个解. ■

注3.2 (3.2)式中的λ满足$\lambda\neq0$, 否则$a_2a_3-a_1a_4=0$, 此时系统(2.3)有多个零点. (3.3)式和(3.4) 式中定义的常数c_1,c_2,c由初始条件确定, 如果初始条件给定, 则c_1, c_2, 和c显然确定.

引理3.3 如果(3.2)式中定义的$f(\lambda)$ 存在一个负根, 则系统(3.1)存在一个轨迹不趋于原点的解.

证 由引理3.1, 若$f(\lambda)=0$ 存在一个负根λ^*, 则系统(3.1)存在形如(3.3)或(3.4)的特解. 由于$\lambda^*<0$ 且c_1, c_2, c都为正数, 因而形如(3.3) 的特解中z_1的轨迹在某时刻附近趋于无穷, 形如(3.4)的特解中z_1和z_2的轨迹在某时刻附近也趋于无穷. 因而, 系统(3.1)存在一个轨迹不趋于原点的解. ■

定理3.4 当$a_1a_4<a_2a_3$时, 系统(3.1) 不是渐近稳定的.

证 由(3.2)式得, 当$a_1a_4<a_2a_3$ 时$f(0)=a_2a_3-a_1a_4>0$. 由于$f(\lambda)$是连续的, 并且当λ趋于负无穷时$f(\lambda)$ 趋于负无穷, 因此$f(\lambda)$至少存在一个负根. 由引理3.3, 系统(3.1) 存在一个轨迹不趋于原点的解. 因此, 系统(3.1)不是渐近稳定的. ■

注3.5 定理3.4表明若系统(3.1)渐近稳定, 则$a_1a_4>a_2a_3$.

下面我们在条件$a_1a_4>a_2a_3$下分析系统(3.1) 的稳定性. 首先, 我们给出系统(3.1) 不是渐近稳定的一个条件.

定理3.6 当$a_1\geq0,a_4\geq0$时, 若$a_1a_4>a_2a_3$, 则系统(3.1)不是渐近稳定的.

证 1) 当$a_1=a_4=0$时, 由$a_1a_4>a_2a_3$ 得$a_2a_3<0$. 构造李亚普洛夫函数$V(z)=-\frac{a_3}{(p+1)a_2}z_1^{p+1}+\frac{1}{p+1}z_2^{p+1}$, 因为$a_2a_3<0$, 所以$V(z)$是正定的. $V(z)$关于时间的导数为$\dot{V}(z)=-\frac{a_3}{a_2}a_2z_1^pz_2^p+a_3z_1^pz_2^p=0$, 此时系统(3.1)是一个振荡器, 即不是渐近稳定的.

2) 当a_1,a_4一零一正时, 由$a_1a_4>a_2a_3$ 得$a_2a_3<0$, 不失一般性, 设$a_1>0,a_4=0$, 构造李亚普洛夫函数$V(z)=-\frac{a_3}{(p+1)a_2}z_1^{p+1}+\frac{1}{p+1}z_2^{p+1}$, 由$a_2a_3<0$得$V(z)$是正定的.

$V(z)$ 关于时间的导数为$\dot{V}(z) = -\frac{a_3}{a_2}a_1z_1^{2p} - \frac{a_3}{a_2}a_2z_1^pz_2^p + a_3z_1^pz_2^p = -\frac{a_3}{a_2}a_1z_1^{2p} \geq 0$. 当$z_1 \neq 0$时$\dot{V}(z) > 0$, 因而对任意$z \in \mathbb{R}^2 \setminus \{z_1 = 0\}$有$V(z) > 0$且$\dot{V}(z) > 0$, 由定理2.3 得系统(3.1)不是渐近稳定的.

3)当$a_1 > 0, a_4 > 0$时. 若$a_2a_3 > 0$, 不失一般性, 设$a_2 > 0, a_3 > 0$. 构造李亚普洛夫函数$V(z) = \frac{a_3a_4}{2}z_1^2 - a_2a_3z_1z_2 + \frac{a_1a_2}{2}z_2^2$, 由$a_1a_4 > a_2a_3$得$a_1a_4a_2a_3 > (a_2a_3)^2$, 因而$V(z)$正定. $V(z)$关于时间的导数为$\dot{V}(z) = a_3(a_1a_4 - a_2a_3)z_1^{p+1} + a_2(a_1a_4 - a_2a_3)z_2^{p+1}$. 当$a_1a_4 > a_2a_3$时, 对任意$(z_1, z_2) \neq (0,0)$ 有$\dot{V} > 0$, 由定理2.3得系统(3.1)不是渐近稳定的.

若$a_2a_3 = 0$, 显然系统(3.1)不是渐近稳定的.

若$a_2a_3 < 0$, 构造李亚普洛夫函数$V(z) = -\frac{a_3}{(p+1)a_2}z_1^{p+1} + \frac{1}{p+1}z_2^{p+1}$, 由$a_2a_3 < 0$得$V(z)$是正定的. $V(z)$关于时间的导数为$\dot{V}(z) = -\frac{a_3}{a_2}a_1z_1^{2p} - \frac{a_3}{a_2}a_2z_1^pz_2^p + a_3z_1^pz_2^p + a_4z_2^pz_2^p = -\frac{a_3}{a_2}a_1z_1^{2p} + a_4z_2^{2p}$, 进而对任意$(z_1, z_2) \neq (0,0)$有$\dot{V}(z) > 0$, 由定理2.3 得系统(3.1)不是渐近稳定的. ■

定理3.6表明, a_1非负且a_4也非负时, 若$a_1a_4 > a_2a_3$, 则系统(3.1)不是渐近稳定的. 下面我们讨论a_1和a_4至少有一个为负数时, 系统(3.1) 渐近稳定的条件.

定理3.7 (i) 当$a_1 < 0, a_4 > 0$时, 若$a_1a_4 > a_2a_3$ 且$a_1^{p+1} > -a_2a_3^p$, 则系统(3.1) 是渐近稳定的;

(ii)当$a_1 > 0, a_4 < 0$时, 若$a_1a_4 > a_2a_3$且$a_4^{p+1} > -a_2^pa_3$, 则系统(3.1)是渐近稳定的.

证 (i)构造李亚普洛夫函数$V(z) = \frac{1}{2}z_1^2 + az_1z_2 + \frac{b}{2}z_2^2$, 其中$a = \frac{pa_1a_2}{a_1a_4-(p+1)a_2a_3}$, $b = \frac{-pa_1^2a_2}{a_3(a_1a_4-(p+1)a_2a_3)}$. 由$a_1a_4 > a_2a_3$可得$a^2 < b$, 从而$V(z)$是正定的. $V(z)$ 关于时间的导数为

$$\begin{aligned}\dot{V}(z) &= z_1\dot{z}_1 + az_1\dot{z}_2 + az_2\dot{z}_1 + bz_2\dot{z}_2\\&= (a_1 + aa_3)z_1^{p+1} + (aa_2 + ba_4)z_2^{p+1} + (a_2 + aa_4)z_1z_2^p + (aa_1 + ba_3)z_1^pz_2.\end{aligned}$$

令$K = \frac{a_1a_4-a_2a_3}{a_1a_4-(p+1)a_2a_3} > 0$, 得

$$\begin{aligned}\dot{V}(z) &= a_1Kz_1^{p+1} - \frac{pa_1a_2}{a_3}Kz_2^{p+1} + (p+1)a_2Kz_1z_2^p\\&= -(p+1)\frac{a_1a_2}{a_3}K\left(\frac{p}{p+1}(z_2^p)^{\frac{p+1}{p}} - \frac{a_3}{a_1}(z_2^p)z_1 - \frac{a_3}{(p+1)a_2}z_1^{p+1}\right).\end{aligned}$$

又因为$a_1^{p+1} > -a_2a_3^p$, 即$\left(-\frac{a_3}{a_1}\right)^{p+1} < \left(-\frac{a_3}{a_2}\right)$, 借助引理2.5得$\dot{V}(z) < 0$, 由定理2.2得, 系统(3.1) 是渐近稳定的.

(ii)构造李亚普洛夫函数$V(z) = \frac{1}{2}z_2^2 + az_1z_2 + \frac{b}{2}z_1^2$, 其中$a = \frac{pa_1a_2}{a_1a_4-(p+1)a_2a_3}$, $b = \frac{-pa_1^2a_2}{a_3(a_1a_4-(p+1)a_2a_3)}$. 同理(i)的证明, 可得当$a_1a_4 > a_2a_3$且$a_4^{p+1} > -a_2^pa_3$时系统(3.1)是渐近稳定的. ■

定理3.8 当$a_1 < 0, a_4 < 0$时, 非线性系统(3.1) 是渐近稳定的充要条件为$a_1a_4 > a_2a_3$.

证 (充分性) 1) 当$a_2a_3 < 0$时, 构造李亚普洛夫函数$V(z) = -\frac{a_3}{(p+1)a_2}z_1^{p+1} + \frac{1}{p+1}z_2^{p+1}$, 由$a_2a_3 < 0$得$V(z)$0正定. $V(z)$关于时间的导数为$\dot{V}(z) = -\frac{a_3}{a_2}a_1z_1^{2p} - \frac{a_3}{a_2}a_2z_1^pz_2^p + a_3z_1^pz_2^p + a_4z_2^{2p} = -\frac{a_3}{a_2}a_1z_1^{2p} + a_4z_2^{2p}$, 进而对任意$(z_1, z_2) \neq (0,0)$有$\dot{V}(z) > 0$. 由定理2.2 得, 系统(3.1) 是渐近稳定的.

2) 当 $a_2a_3=0$ 时, 构造李亚普洛夫函数$V(z)=\frac{\widehat{a}}{p+1}z_1^{p+1}+\frac{\widehat{b}}{p+1}z_2^{p+1}$, 其中 $\widehat{a}>0,\widehat{b}>0$, $V(z)$ 关于时间的导数为$\dot{V}(z)=\widehat{a}a_1z_1^{2p}+(\widehat{a}a_2+\widehat{b}a_3)z_1^pz_2^p+\widehat{b}a_4z_2^{2p}$, 由 $a_2a_3=0$ 得存在满足条件的正数 $\widehat{a}$ 与 $\widehat{b}$ 使得 $\dot{V}(z)<0$. 由定理 2.2 得系统 (3.1) 是渐近稳定的.

3) 当 $a_2a_3>0$ 时, 不失一般性, 设 $a_2>0,a_3>0$, 构造李亚普洛夫函数$V(z)=-\frac{a_3a_4}{2}z_1^2+a_2a_3z_1z_2-\frac{a_1a_2}{2}z_2^2$, 由 $a_1a_4>a_2a_3$ 得 $a_1a_4a_2a_3>(a_2a_3)^2$, 因而 $V(z)$ 正定. 并且

$$\begin{aligned}\dot{V}(z)&=(a_2a_3^2-a_1a_3a_4)z_1^{p+1}+(a_2^2a_3-a_1a_2a_4)z_2^{p+1}\\&=a_3(a_2a_3-a_1a_4)z_1^{p+1}+a_2(a_2a_3-a_1a_4)z_2^{p+1},\end{aligned}$$

进而对任意 $(z_1,z_2)\neq(0,0)$ 有 $\dot{V}(z)>0$. 由定理 2.2 得系统 (3.1) 是渐近稳定的.

(必要性) 只需要证明当 $a_1a_4<a_2a_3$ 时, 系统 (3.1) 不是渐近稳定的. 由定理 3.4 得必要性条件成立. ■

命题3.9 当 $a_1+a_4<0,a_1a_4=0$ 时, 系统 (3.1) 渐近稳定的充要条件为 $a_1a_4>a_2a_3$.

证 (充分性) 不失一般性, 设 $a_1<0,a_4=0$. 构造李亚普洛夫函数$V(z)=-\frac{a_3}{(p+1)a_2}z_1^{p+1}+\frac{1}{p+1}z_2^{p+1}$, 可得 $\dot{V}(z)=-\frac{a_1a_3}{a_2}z_1^{2p}$, 于是 $\dot{V}(z)\leq0$, 由定理 2.2 得系统 (3.1) 渐近稳定.

(必要性) 由定理 3.4 得必要性条件成立. ■

4 例子

例4.1 考虑系统 (3.1). 当 $a_1=a_4=0$, $a_2a_3<0$ 时, 由定理 3.6 的证明 (i) 得系统 (3.1) 是一个振荡器. 例如, 当 $a_2=1$, $a_3=-\frac{1}{2}$, $a_1=a_4=0$, $p=3$ 时, 系统 (3.1) 的数值仿真如图1所示.

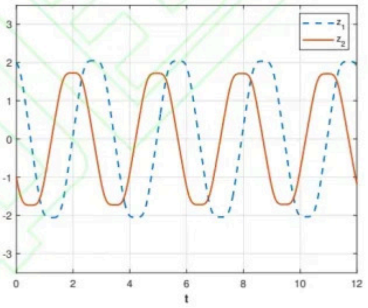

图1 $a_1=a_4=0$, $a_2=1$, $a_3=-0.5$, $p=3$ 及 $z(0)=(2,-1)^T$ 时系统 (3.1) 的振荡解

(Figure 1 Oscillating solution of (3.1) with $a_1=a_4=0$, $a_2=1$, $a_3=-0.5$, $p=3$ and $z(0)=(2,-1)^T$)

本文得到的稳定性条件可以被用来分析一些特殊系统的控制器设计问题. 下面给出两个具体的例子来进行说明.

例4.2 考虑系统

$$\begin{cases}\dot{x_1}(t)=-4x_1^3(t)-x_2^3(t),\\ \dot{x_2}(t)=u+x_2^3(t).\end{cases}\tag{4.1}$$

根据定理3.7, 可以设计如下控制器

$$u = k_1 x_1^3(t) + k_2 x_2^3(t), \tag{4.2}$$

将(4.2)代入(4.1)得到

$$\begin{cases} \dot{x_1}(t) = -4x_1^3(t) - x_2^3(t), \\ \dot{x_2}(t) = k_1 x_1^3(t) + (k_2+1)x_2^3(t). \end{cases} \tag{4.3}$$

当 k_1 和 k_2 满足$k_1 > 0, k_2 + 1 > 0$时, 由定理3.7, 若 $(-4)(k_2+1) > -k_1$ 且 $(-4)^4 > k_1^3$, 则系统(4.3)渐近稳定. 当$k_1 = 3$, $k_2 = -\frac{1}{2}$ 且初始条件 $(x_1(0), x_2(0)) = (-1, 2)$ 时, 系统(4.3)的状态轨迹如图2所示.

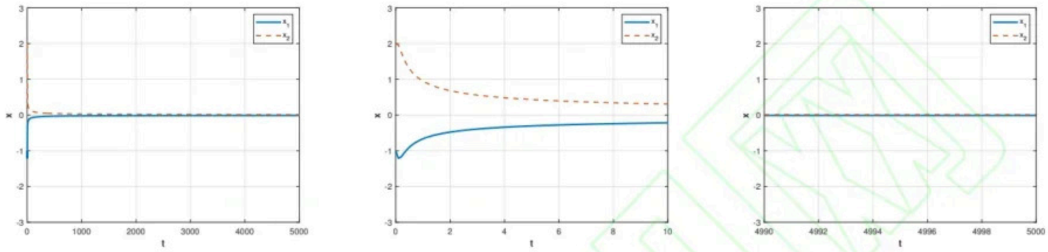

图2 $(k_1, k_2) = (3, -\frac{1}{2})$ 及 $x(0) = (-1, 2)^T$ 时系统(4.3)的状态轨迹

(Figure 2 Trajectory of system (4.3) with $(k_1, k_2) = (3, -\frac{1}{2})$ and $x(0) = (-1, 2)^T$)

例4.3 考虑系统

$$\begin{cases} \dot{x_1}(t) = -\theta_1 x_1^3(t) + \theta_2 x_2^3(t), \\ \dot{x_2}(t) = u, \end{cases} \tag{4.4}$$

其中θ_1, θ_2是有界未知正参数. 假设

$$a_1 \le \theta_1 \le b_1, a_2 \le \theta_2 \le b_2, \tag{4.5}$$

其中a_1, b_1, a_2 和 b_2 是已知常数. 由定理3.8 得, 可以设计控制器

$$u = k_1 x_1^3(t) - k_2 x_2^3(t), \tag{4.6}$$

其中k_1, $k_2 > 0$. 当控制增益 k_1 和 k_2 满足 $(-\theta_1)(-k_2) > \theta_2 k_1$, 即 $k_1/k_2 < \theta_1/\theta_2$ 时, 由边界条件(4.5) 得, 只要 $k_1/k_2 < \min(\theta_1/\theta_2) = a_1/b_2$, 则控制器(4.6) 能保证系统(4.4)渐近稳定. 例如, 当 $a_1 = 2$, $b_2 = 1$ 时，取 $k_1 = 1$, $k_2 = 2$, $\theta_1 = a_1 = 2$, 且 $\theta_2 = b_2 = 1$, 则系统(4.4)的解如图3所示.

5 结论

本文研究了一类平面非线性系统的稳定性问题, 给出了稳定的若干条件. 特别地, 当 $p = q$ 且 $a_1 < 0, a_4 < 0$ 时, 得到了系统渐近稳定的充要条件, 并且利用特解法证明了系统的不稳定性. 特解方法在研究系统的不稳定性方面具有重要意义, 借助这一方法, 可直观地分析更为一般的非线性系统的不稳定性. 对于本文所研究的系统, 其稳定的充分必要条件以及非齐次条件下系统的稳定性有待进一步研究. 此外,

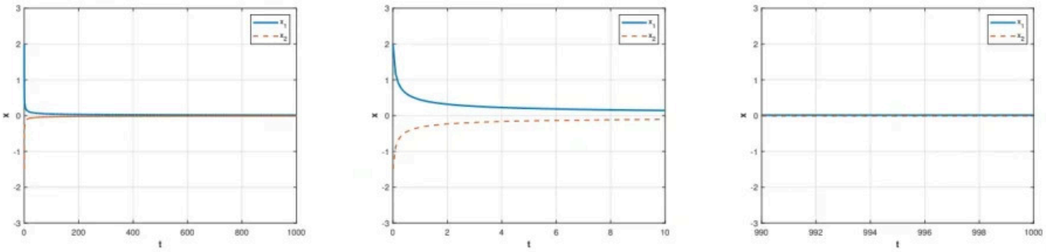

图3 $(k_1,k_2)=(1,2),(\theta_1,\theta_2)=(2,1)$ 及 $x(0)=(2,-1.5)^T$ 时系统 (4.4) 的状态轨迹
(Figure 3 Trajectory of system (4.4) with $(k_1,\ k_2)=(1,2)$, $(\theta_1,\ \theta_2)=(2,1)$ and $x(0)=(2,-1.5)^T$)

对于更高阶且更复杂的非线性系统, 寻找合适的方法研究其稳定性仍然是一个值得探究的课题. 目前, 这方面的工作正在研究中.

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